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FREE-FLIGHT PROBE FOR PLASMA DIAGNOSTICS

Submitted to

Air Force Office of Scientific Research
Plasma Physics Branch
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Research was carried out on the development and application of a new diagnostic technique - the Free Flight Probe (FFP) - to measure magnetic fields in the interior of hot plasmas. Data obtained for both vacuum and plasma fields using this diagnostic on the UW Helicity Injected Tokamak was analyzed to determine n=1 mode structure. The response function of the diagnostic's ellipsometer was investigated analytically and experimentally.

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FREE FLIGHT PROBE FOR PLASMA DIAGNOSTICS

SUMMARY

This document is the final technical report on Air Force Office of Scientific research Grant # F49620-94-1-0030. This project was carried out to develop a new diagnostic probe, commonly referred to as the "transient internal probe" (TIP), for measuring interior magnetic field profiles in hot plasmas. The work was conducted in the period October 15, 1993 to November 14, 1997, with the final year being a no-cost extension of the original grant.

The TIP diagnostic is a novel method for probing the interior of hot magnetic plasmas that are inaccessible with ordinary stationary probes. A small probe constructed of a magneto-optic material is fired through a hot plasma at high velocity. During its transit the probe is illuminated with polarized laser radiation, which passes through the probe and is retroreflected back to the source by means of a reflector mounted on the probe's back face. In the double pass through the probe, the light's polarization is rotated in proportion to the local magnetic field, and resolution of the polarization angle of the return light by a detection system remote from the plasma allows accurate determination of the magnetic field. Under this grant research was carried out to develop TIP into a reliable and accurate plasma diagnostic, apply it to determine interior fields in the University's Helicity Injected Tokomak (HIT), and to explore means of expanding the range of variables measurable with TIP.

The thrust of this program has been the development of several key component technologies. A light gas gun has been constructed which accelerates 50-caliber projectiles to 2.0 km/sec. A particularly significant milestone was the development of a sabot-stripping and gas-isolation system, capable of separating the Verdet probe from its protective sabot following acceleration, discarding the sabot (which would otherwise rapidly ablate and contaminate the plasma), and keeping the introduction of gun gases into the plasma to < 0.4 Torr-liter. Despite the enormous range of gas pressures and forces during the launch process, this scheme is capable of maintaining the integrity and orientation of the relatively fragile rectangular glass probe with high reliability (≈90%).

A laser illumination and polarimetry system has been developed which has an ultimate resolution of 0.03°. The capability of the diagnostic has been demonstrated by

measuring the field of a 2 kG static magnet via passage of a 2 km/sec Verdet probe and comparing the result with measured using a of a Hall probe, translated along the TIP probe's trajectory. This demonstration yielded an agreement of $\approx$ 40 Gauss over the entire spatial extent of the field, at $\leq$ 1 cm resolution. Finally the diagnostic has been applied for the measurements of the internal field of the ~ 80 eV HIT plasma, where resolution was observed to be $\approx$ 20 Gauss for local field variations, and $\pm$ 200 Gauss in absolute field magnitude (peak magnitude of 8 kG).

A novel design was developed for using a Verdet probe to measure the component of magnetic field *transverse* to the probe path. This design is much simpler and in principle more robust than earlier concepts. Tests of preliminary versions of this probe have not yet been successful, but point to design improvements which may lead to practical transverse-field probes.

The success of this program in proving the utility of TIP has generated a strong interest among the plasma research community in applying the diagnostic to a variety of plasmas.

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FREE FLIGHT PROBE FOR PLASMA DIAGNOSTICS

T.R. Jarboe and A.T. Mattick
University of Washington

1. INTRODUCTION

This document is the final technical report on Air Force Office of Scientific research Grant # F49620-94-1-0030. This project was carried out to develop a new diagnostic probe, commonly referred to as the "transient internal probe" (TIP), for measuring interior magnetic field profiles in hot plasmas. The work was conducted in the period October 15, 1993 to November 14, 1997, with the final year being a no-cost extension of the original grant.

This introduction presents the background for this project, the research objectives, and a summary of the research results. Also included is a list of project personnel, and a list of the publications resulting from this work. The following chapters detail the progress in specific aspects of the development of this diagnostic and its application to measure magnetic fields in the University of Washington Helicity Injected Tokomak (HIT).

1.1 BACKGROUND

The measurement of internal magnetic fields in high-temperature plasmas is critical to understanding of plasma equilibrium, transport, and stability. Many processes of interest take place over length scales an order of magnitude or more less than plasma dimensions, and at time scales down to sub-microsecond levels. Despite the importance of having high-spatial and/or time resolution profiles of internal fields, no conventional diagnostic has been able to provide this. For example, external measurements can provide global information on plasma characteristics, yet cannot resolve interesting processes that have sub-diameter spatial variations. Internal measurements that use the motional Stark effect are typically limited to bandwidths in the kilohertz range, due to the low signal-to-noise of this diagnostic.[1,2] Heavy-ion beam probes have been used with some success for measurement of plasma internal fields,[3] but require inordinate beam energies to reach the center of the plasma. Moreover, in both of these internal diagnostics, the current profile and toroidial field must be accurately known to extract poloidal field information, and niether is useful for non-Tokomak configurations. The use of physical probes has

been restricted to the edge regions of plasmas, because of rapid ablation, and consequent "poisoning" of the plasma. Typically, such probes are inserted and withdrawn from the edge region on time scales of 50-100 msec [4], and can provide only limited information on *internal* fields.

The transient internal probe is a new approach that for the first time allows high-bandwidth, high-spatial resolution measurement of the magnetic field profile across the entire diameter of a high-temperature plasma. In the course of this project, this diagnostic has been applied to determine the toroidial field across the diameter of the University of Washington Helicity Injected Tokomak, and has resolved the spatial profile of the n=1 plasma mode, which is a key mechanism of relaxation and current drive.[5,6] This represents a breakthrough in plasma diagnostics, as the spatial resolution of the n=1 mode is not accessible by other means.

The Transient Internal Probe (TIP) [Refs. 5-15] derives its unique capability from the use of a small, free-flying, magneto-optic probe, which is launched through a plasma at speeds of several km/sec. As illustrated in Fig. 1.1, the probe is continuously illuminated by a polarized laser beam. As the beam traverses the probe the polarization is rotated in proportion to the strength of the local magnetic field, and the beam is retroreflected back to a detection system, which measures the absolute polarization to high precision for determination of the field. Probes may also be constructed of electro-optic material for high-resolution measurement of *electric* fields in plasmas. Communication of field information via narrowband laser radiation has advantages of high-sensitivity, high-bandwidth, and minimal interference by the plasma. The detection system can be placed remotely from the vicinity of a plasma machine for isolation from noise sources.

Magneto-optic (Verdet) materials are readily available to fabricate probes having high sensitivity to magnetic fields at high spatial resolution. The rotation angle of polarization making a double-pass through a probe is given by $\varphi = 2LVB_z$, where L is the probe length, V the Verdet coefficient, and B_Z is the field component in the probe's direction of travel. The L=1 cm, Tb-doped borosilicate glass (V=0.0095 deg/cm -Gauss) probes commonly used in the U.W. TIP facility , have a sensitivity of $\varphi \approx 0.02$ deg/Gauss; the demonstrated resolution of 0.3° for the polarimeter results in a field resolution of $\approx$16 Gauss. This field resolution and the 1-cm spatial resolution are both very high for any plasma diagnostic. The temporal resolution of the diagnostic is limited only by the detection system and S/N, and the current system has a bandwidth of $\approx$ 10 MHz, orders of magnitude higher than that of classical internal field diagnostics, such as motional Stark.

The basis of the TIP approach is that the high speed probe can transit a hot plasma in durations short enough that significant evaporation of the probe will not occur over the

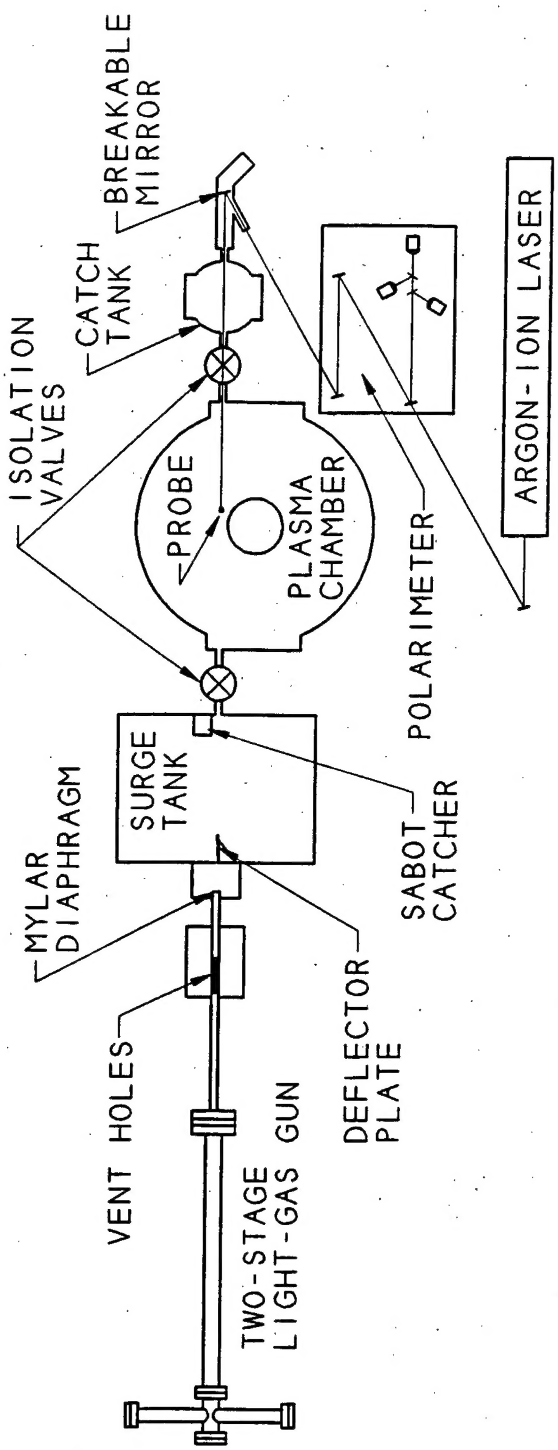

Figure 1.1 Overview of Transient Internal Probe Concept.

measurement period. The heat flux on a surface in a plasma of temperature T, electron density n_e, and ion mass m_i,: [16]

$$Q = n_e kT\sqrt{kT/2\pi m_i}\,f\cdot[4+\tfrac{1}{2}\ln(m_i/m_e)-\ln(f)]$$

where f is an enhancement factor due to ion attraction, depending on the ratio of debye shielding length to the dimension of the surface, and tabulated in Ref. 17. For TIP probes, where this ratio is ≥ 100, f is relatively insensitive to geometry and has a value $f \approx 1.7$ for all plasma conditions of interest. In this case, we have:

$$Q(MW/m^2) \approx 0.8\frac{n_e}{10^{14}/cm^3}T^{3/2}(eV)\frac{1+\ln(M_i)/14.5}{\sqrt{M_i}},$$

where the reference density of $10^{14}/cm^3$ is representative, and M_i is ion mass in a.m.u. At a given flux Q, the time for the surface of a thick cladding to reach a temperature T* is $t_b = \frac{\pi}{4}\rho c\kappa(T^*-T_i)^2/Q^2$, where ρ, c, and κ are the density, specific heat and thermal conductivity, respectively, and T_i is the initial probe temperature (300K). A conservative upper limit for T* is the saturation temperature at which the vapor pressure is ≈ 1 Torr.

For measurements on HIT, (density $n \approx 10^{13}/cm^3$, temperature up to ≈ 80 eV, transit time ≈0.5 msec), the glass Verdet probe used suffered no appreciable ablation. For higher-temperature plasmas, a cladding of diamond or other refractory material would be used to assure survival, and provide internal B-field data across the plasma. Figure 1.2 shows plasma temperatures and densities yielding belief times of 100, 200, and 500 μsec for diamond-clad probes. It is seen that TIP probes are indeed usable for a wide range of high heat flux plasmas, such as DIII-D and NSTX.

In summary, the use of a high-speed magneto-optic probe offers a unique and enabling approach for measurement of internal magnetic and electric fields in high-temperature plasmas. The successful development of this diagnostic and its application to measure magnetic fields in HIT under this grant represents a breakthrough in plasma diagnostics. The following subsections summarize the objectives and results from this research. Details of the research effort are presented in the following chapters, and in appendices A-C, containing the journal articles published on this project.

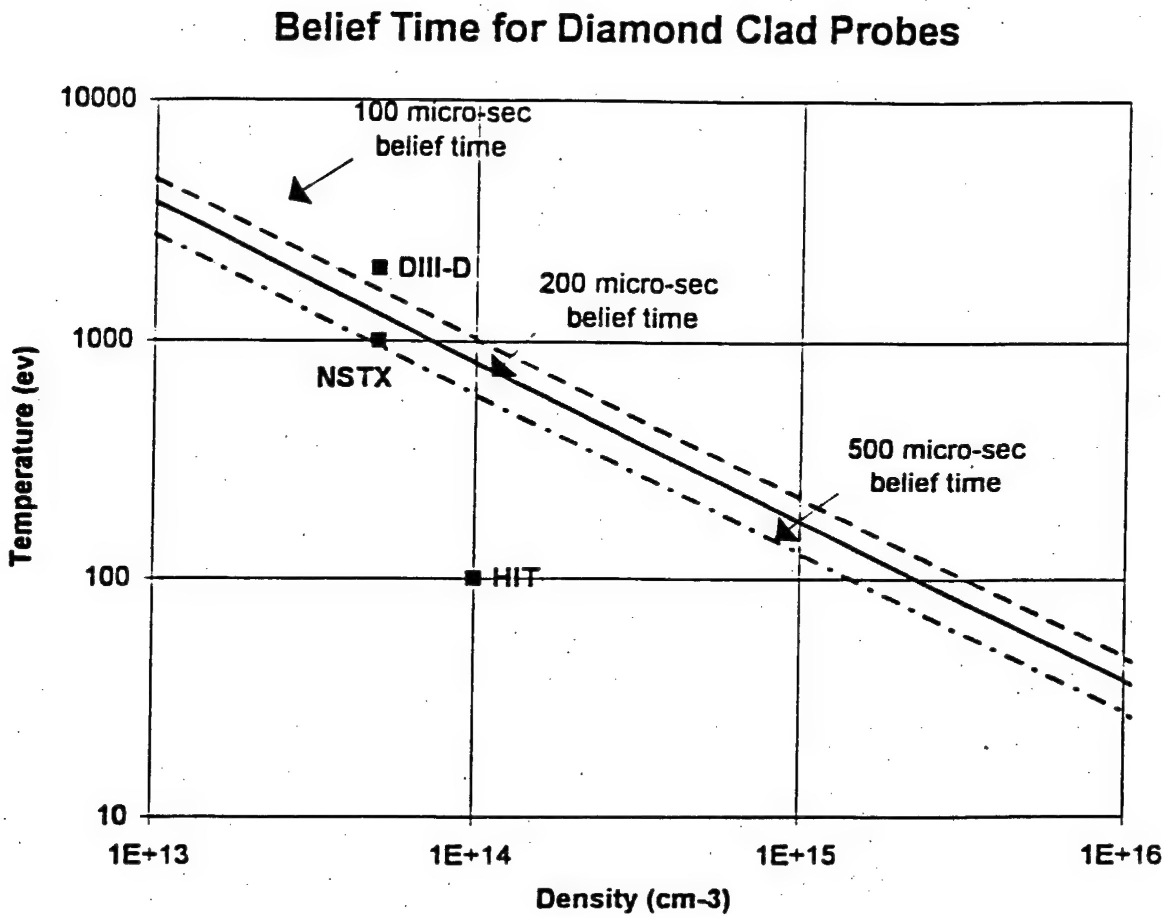

Figure 1.2 Plot of constant "belief time" as a function of plasma temperature and density for diamond clad probes.

1.2 RESEARCH OBJECTIVES

Initial development of the TIP diagnostic was carried out under a previous AFOSR grant in the period 1990 - 1993. In that work, a light gas gun was designed and constructed and shown to be capable of launching probes to speeds in the range 2-3 km/sec. A polarimeter was also designed and constructed for analyzing the polarization of the return beam from a probe for magnetic field determination, and was successfully tested by dropping a Verdet probe through a known magnetic field. The TIP-derived field agreed with the field measured with a Hall probe to within the 1% accuracy of the Hall probe. An evacuated gas-stripping tank was fitted to the gun, which provided a test bed for evaluation methods of sabot stripping, and photographing the probe/sabot in flight.

While these efforts represented a significant step in the evolution of the TIP diagnostic, several technical challenges remained in order to actually apply the diagnostic to the measurement of magnetic fields. Among these were:

1) Development of a method of stripping the sabot from the probe in a manner that minimizes perturbations to probe trajectory and preserves the integrity of the probe.
2) Development and demonstration of a system that can keep the admission of gun gases into a plasma chamber to a very low level.
3) Demonstration of accurate, high-bandwidth measurement of magnetic fields using a Verdet probe travelling at speeds of several km/sec.

These comprised the research objectives of the initial phase of the program described in this report. With successful accomplishment of these steps a key goal of the program was:

4) Utilize the TIP diagnostic to measure the internal magnetic field across the diameter of the HIT plasma. This endeavor would represent the first such measurement at high resolution and high bandwidth in the interior of a hot plasma, and would provide critical information on the structure of the n=1 plasma mode.

In order to expand the range of information obtainable from this diagnostic approach, the following additional objectives were set, as outlined in the original proposal:

5) Develop a design for, and test, a probe that could measure transverse magnetic field components.
6) Develop and test TIP probes that can simultaneously measure 3 independent components of magnetic and electric fields in plasmas.

In the course of this project, objectives 1-4 were successfully accomplished, resulting in a new diagnostic technique that can be applied widely to obtain new information that is

critical for understanding stability and transport in plasmas. Progress was made in objective 5, in that a new design for optical measurement of transverse fields was developed. Tests of a prototype did not succeed, however, due to the limited strength of this probe under high acceleration. Lack of resources prevented the research team from pursuing objective 6.

1.3 SUMMARY OF RESEARCH RESULTS

The thrust of this program has been the development of several key component technologies for TIP, and the application of the diagnostic to measure the magnetic field in a hot plasma. A summary of the achievements in the development of TIP is given below:

- A light-gas gun has been developed which accelerates Verdet probes to 2 km/sec, with the ultimate capability of reaching speeds above 4 km/sec. The gun firing system is capable of a jitter of < ±0.7 msec between the digital firing signal and probe arrival at the entrance to the plasma chamber, facilitating coordination of plasma initiation and TIP B-field measurements.
  This work is been published in Refs. 8, 10, and 11.

- A method has been developed for separating the sabot from the Verdet probe, preventing sabot material from entering and contaminating the plasma. This gasdynamic separation can successfully launch a rectangular glass Verdet probe into a plasma with minimal probe rotation with a 90% reliability.[5,14]

- The diagnostic includes a system for removal of gun gases from the probe trajectory, limiting the inflow of these gases into the plasma to levels that do not interfere with plasma operation. This system effectively reduces the gas pressure by 12 orders of magnitude between the gun and the plasma chamber.[5,14]

- A probe/polarimeter system has been developed which is capable of resolution of axial magnetic field to ± 20 gauss, independent of field magnitude.[9,11]

- A proof-of-concept experiment, where a high-speed probe traversed the field of a fixed magnet, demonstrated excellent agreement between the TIP-derived field and that measured with a Hall probe.[13,14]

- Application of the diagnostic to measure the toroidial field in the U.W. Helicity Injected Tokomak machine succeeded in determining, for the first time, the internal field in a hot plasma at high spatial and temporal resolution.[5] This measurement yielded important data on the geometry of the n=1 mode (f=50 kHz), key to the mission of the experiment.[6]

- A novel design was developed for using a Verdet probe to measure the component of magnetic field *transverse* to the probe path. This design is much simpler and in principle more robust than earlier concepts. Tests of preliminary versions of this probe have not yet been successful, but point to design improvements which may lead to practical transverse-field probes.[15]

These achievements are discussed in detail in the following chapters.

1.4 PROJECT PERSONNEL

Dr. Tom Jarboe, Professor of Aeronautics and Astronautics, was principal investigator for the program, with overall responsibility for technical management. Dr. Tom Mattick, Associate Professor of Aeronautics and Astronautics, served as a faculty investigator, and supervised the experimental program. The construction and experimental tests of the free flight probe were carried out by graduate students Jim Galambos, Ph.D. candidate in nuclear engineering, and Mike Bohnet, Ph.D. candidate in Aeronautics and Astronautics, assisted by two undergraduate research assistants. Dr. Galambos and Dr. Bohnet both completed their Ph.D. degrees with support of this grant, and their theses, listed in the following section, report on specific aspects of the development of the transient internal probe and its application for measurement of magnetic fields in HIT.

1.5 PUBLICATIONS

Below are listed the publications and presentations at technical meetings of free-flight probe research that were supported fully or in part by this grant.

Peer-reviewed publications:

"The transient internal probe: A novel method for measuring internal magnetic field profiles," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, A.T. Mattick, and G.G. Spanjers, *Rev. Sci. Inst.* **66**, p. 1197 (1995).

"Magnetic field measurements using the transient internal probe," J.P. Galambos, M.A. Bohnet, T.R. Jarboe, and A.T. Mattick, *Rev. Sci. Inst.* **67**, p. 469 (1996).

"Internal magnetic field measurements on the helicity injected tokamak using the transient internal probe," J.P. Galambos, M.A. Bohnet, T.R. Jarboe, and A.T. Mattick, *Rev. Sci. Inst.* **68**, 385 (1997).

"A high-speed ellipsometer for the measurement of internal magnetic fields in hot plasmas," M.A. Bohnet, A.T. Mattick and T.R. Jarboe, submitted to *Journal of the Optical Society of America - A*.

Presentations at technical meetings:

"Development of Transient Internal Probe (TIP) magnetic field diagnostic," J.P. Galambos, M.A. Bohnet, T.R. Jarboe,and A.T. Mattick, APS 35th Annual Plasma Physics Meeting, St. Louis, MO, Nov. 1-5, 1993.

"The transient internal probe: A novel method for measuring internal magnetic field profiles," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, A.T. Mattick and G.G. Spanjers, APS 10th Topical Conference on High Temperature Plasma Diagnostics, Rochester, NY, May 8-12, 1994.

"Development of Transient Internal Probe (TIP) magnetic field diagnostic," J.P. Galambos, M.A. Bohnet, T.R. Jarboe,and A.T. Mattick, 1994 IEEE International Conference on Plasma Science, Santa Fe, NM, June 6-8, 1994.

"Magnetic field measurements at high velocity using a two-stage light-gas gun," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, and A.T. Mattick, 45th Aeroballistic Range Association Meeting, Huntsville, AL, Oct. 10-14, 1994.

"Development of transient internal probe magnetic field diagnostic," J.P. Galambos, M.A. Bohnet, T.R. Jarboe,and A.T. Mattick, 36th Annual meeting, Division of Plasma Physics, American Physical Society, Minneapolis, Nov. 7-11, 1994.

"Magnetic field measurements using the transient internal probe," J.P. Galambos, M.A. Bohnet, T.R. Jarboe,and A.T. Mattick, 1995 IEEE International Conference on Plasma Physics, Madison, WI, June 5-8, 1995.

"Development of orthogonal transient internal probe," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, and A.T. Mattick, 1995 IEEE International Conference on Plasma Physics, Madison, WI, June 5-8, 1995.

"Development of an orthogonal transient internal probe," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, and A.T. Mattick, 37th Annual APS Plasma Physics Meeting, Louisville, KY, Nov. 6-10, 1995.

"Internal magnetic field measurements on the Helicity Injected Tokamak using the Transient Internal Probe ," J.P. Galambos, M.A. Bohnet, T.R. Jarboe, and A.T. Mattick, 11th Topical Conference on High Temperature Plasma Diagnostics, Monterey, CA, May 12-16, 1996.

"Internal magnetic field measurements on the Helicity Injected Tokamak using the Transient Internal Probe," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, and A.T. Mattick, 1996 IEEE International Conference on Plasma Science, Boston, MA, June 3-5, 1996.

"Recent results of the Helicity Injected Tokomak experiment," T.R. Jarboe, presented at 16th IAEA Fusion Energy Conference, Montreal, Oct. 7-11, 1996.

"Magnetic field measurements on the Helicity Injected Tokomak (HIT) using the transient internal probe (TIP)," M.A. Bohnet, J.P. Galambos, T.R. Jarboe, and A.T. Mattick, 38th Annual APS Plasma Physics Meeting, Denver, CO, Nov. 1996.

"Recent results of the Helicity Injected Tokomak experiment," T.R. Jarboe, presented at the Spherical Torus Workshop, Cullam Lab, England, Dec. 1996.

"Internal magnetic field measurements on HIT," M.A. Bohnet, presented at the U.S. Japan Workshop on Helicity Injection Current Drive, Seattle, WA, Mar. 10-12, 1997.

Graduate theses:

"Measurement of the internal toroidal magnetic field on the helicity injected tokomak using the transient internal probe," J.P. Galambos, Ph.D. thesis, University of Washington Department of Nuclear Engineering, 1996.

"Experimental investigation of the n=1 mode in the helicity injected tokomak using the transient internal probe," M.A. Bohnet, Ph.D. thesis, University of Washington Department of Aeronautics and Astronautics, 1997.

1.6 INTERACTIONS.

The success of this program in proving the utility of TIP has generated a strong interest among the plasma research community in applying the diagnostic to a variety of plasmas. Letters of interest in applying TIP for plasma research have been received from the University of Wisconsin-Madison, Lawrence Livermore Laboratory, and the University of Washington's Redmond Plasma Physics Laboratory. The plasma heat fluxes for these facilities requires a refractory cladding for TIP probes, to be able to measure the spatial variation of field across the entire plasma diameter and to prevent plasma contamination. As an outgrowth of the AFOSR-sponsored program, the research team is currently developing methods for cladding TIP probes in refractory material, and helping to develop a TIP system for Lawrence Livermore Laboratory.

2. PROBE LAUNCH

2.1 LIGHT GAS GUN

A 2-stage light gas gun has been developed which has accelerated TIP projectiles to speeds as high as 2.8 km/sec, with the potential for speeds up to 4.5 km/sec. The gun system has evolved through a number of stages throughout the program to accommodate the needs of sabot-removal and gas-stripping systems. A discussion of earlier versions and tests of gun performance is given in Refs. 8 and 10. The present discussion focuses on the current design, successfully used for plasma field measurements.

The choice of a two-stage gun was made to avoid the complications of using high static pressures (~ 50 ksi). As illustrated in Fig. 2.1, the gun is comprised of transverse driver tubes, a pump tube containing a piston, and a gun barrel. The driver tubes (7.6 cm ID by 56 cm long) are prefilled with nitrogen to 1900 psi with the piston, at its initial placement at the upstream end of the pump tube, making a gas seal for the nitrogen. The pump tube (4 cm ID by 2.44 m long) is prefilled with helium to nominally 73 psi, and is isolated from the nitrogen by bridgeman and o-ring seals on the piston, and from the barrel by a scored diaphragm. The TIP projectile (LEXAN sabot holding the Verdet probe) is initially placed in the breech of the 50 caliber (12.7 mm ID) barrel. The gun is fired by applying high-pressure nitrogen to the back face of the piston, via a fast-opening valve (see below). This moves the piston forward to expose the driver gas, which continues to accelerate the piston and compress the helium. When the helium reaches a pressure of nominally 35 ksi (determined by scoring of the diaphragm) the diaphragm bursts, exposing the projectile to the high-pressure pump gas and accelerating it down the barrel. The operating points have been selected to cause the piston to decelerate nearly to rest by the end of the firing operation (by virtue of helium pressure history), to prevent damage to the piston.

Under the above conditions the gun will accelerate current TIP projectiles (total mass of 2.7 grams) to 1.9 - 2.0 km/sec, fast enough that the probe material will survive transit through the HIT plasma at 80 eV. The probe speed is measured to ± 10 m/sec using signals from passage of the probe through two laser beams transverse to the path, spaced by ≈ 2 m. Earlier versions of the gun using a smaller 30 caliber barrel and smaller projectile mass reached 2.8 km/sec at a peak pump-gas pressure of 50 ksi

A significant achievement was the development of a fast-acting valve that initiates the gun. Previously, an electropneumatic valve was used, with an opening time of a few 10ths of one second. While this relatively long opening time was itself not problematic,

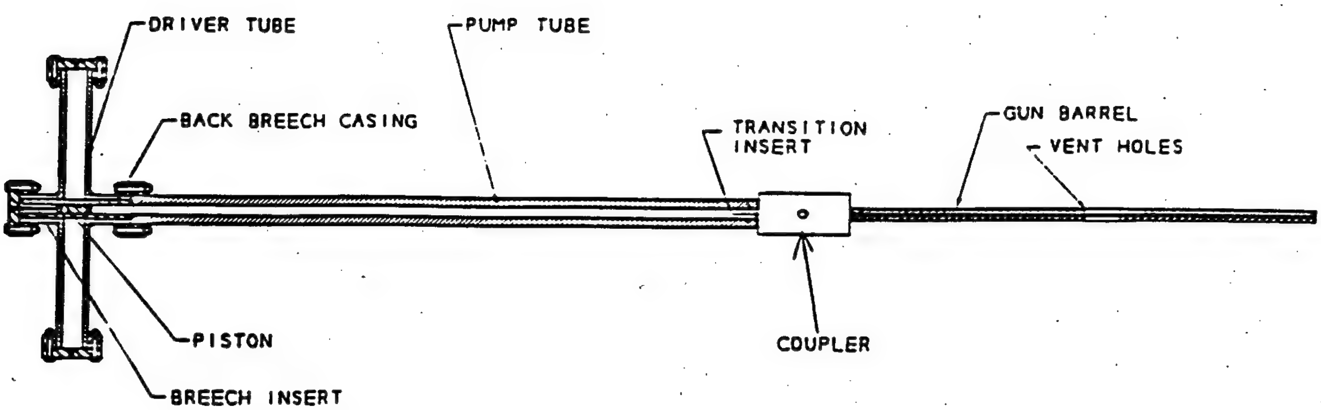

Figure 2.1 TIP Two-stage light gas gun.

the jitter in the duration between the actuation signal and arrival of the probe at the plasma entrance station was several msec, comparable to plasma durations. It was desired to reduce this jitter to below 1 msec to allow accurate coordination between gun initiation and plasma initiation. This was accomplished by using a high-torque stepper motor to drive the ball valve which admits the piston initiation gas. The stepper (200 steps/revolution) positions the valve precisely, a few degrees from the onset of valve opening, prior to firing. An optically isolated digital pulse initiates stepping (500 steps/sec) to open the valve at a very reproducible rate. Using this method, the duration between the pulse rising edge and arrival of the probe at a point 0.5 m downstream of the muzzle is nominally 57 msec with a jitter of less than ± 0.7 msec. This jitter could be reduced by use of a higher-voltage stepper drive system to allow step rates up to 2000 steps/sec.

Another improvement in the gas gun was implementation of a differential threaded coupler for attaching the barrel to the pump tube. The barrel/tube joint must be opened between firings to replace the diaphragm and TIP projectile. A recurring difficulty earlier in the program was variation of the probe trajectory due to misalignment of the barrel that occurred with the previous use of flanges for this joint. The differential coupler provides a uniform compression of the diaphragm, and does not introduce any moments which could misalign or bend the gun barrel.

The 50 caliber, smooth bore barrel is 1.73 m long, and serves both to accelerate the projectile and to separate probe from sabot. The transition in function occurs near mid-barrel where numerous vent holes have been drilled, so that only the first half is used for projectile acceleration. The vented helium is collected by a tank sealed to the barrel by sliding o-rings, and the initial barrel pressure (needed for sabot separation) is controlled via this tank. The barrel is connected to an evacuated expansion tank via a flexible bellows and sliding o-ring seal, resulting in negligible transverse forces that could disrupt alignment. A mylar diaphragm mounted to the muzzle isolates barrel gas from the expansion tank prior to gun operation. This system places strong emphasis on minimizing side forces on the barrel and avoiding transverse disruptions (such as gas flow and mechanical transitions) of the probe and sabot during acceleration. Numerous iterations and tests of gun performance demonstrated the deleterious effects of such disruptions - including probe rotation, misdirection, and even disintegration. The biggest improvement in reliability resulted from replacement of separate, mechanically-joined barrel sections for acceleration and sabot-separation, by a single, vented barrel.

A photograph of the light gas gun is shown in Fig. 2.2. It weighs approximately 1000 lb and is supported by hydraulic lifts that facilitate accurate positioning. Setup and

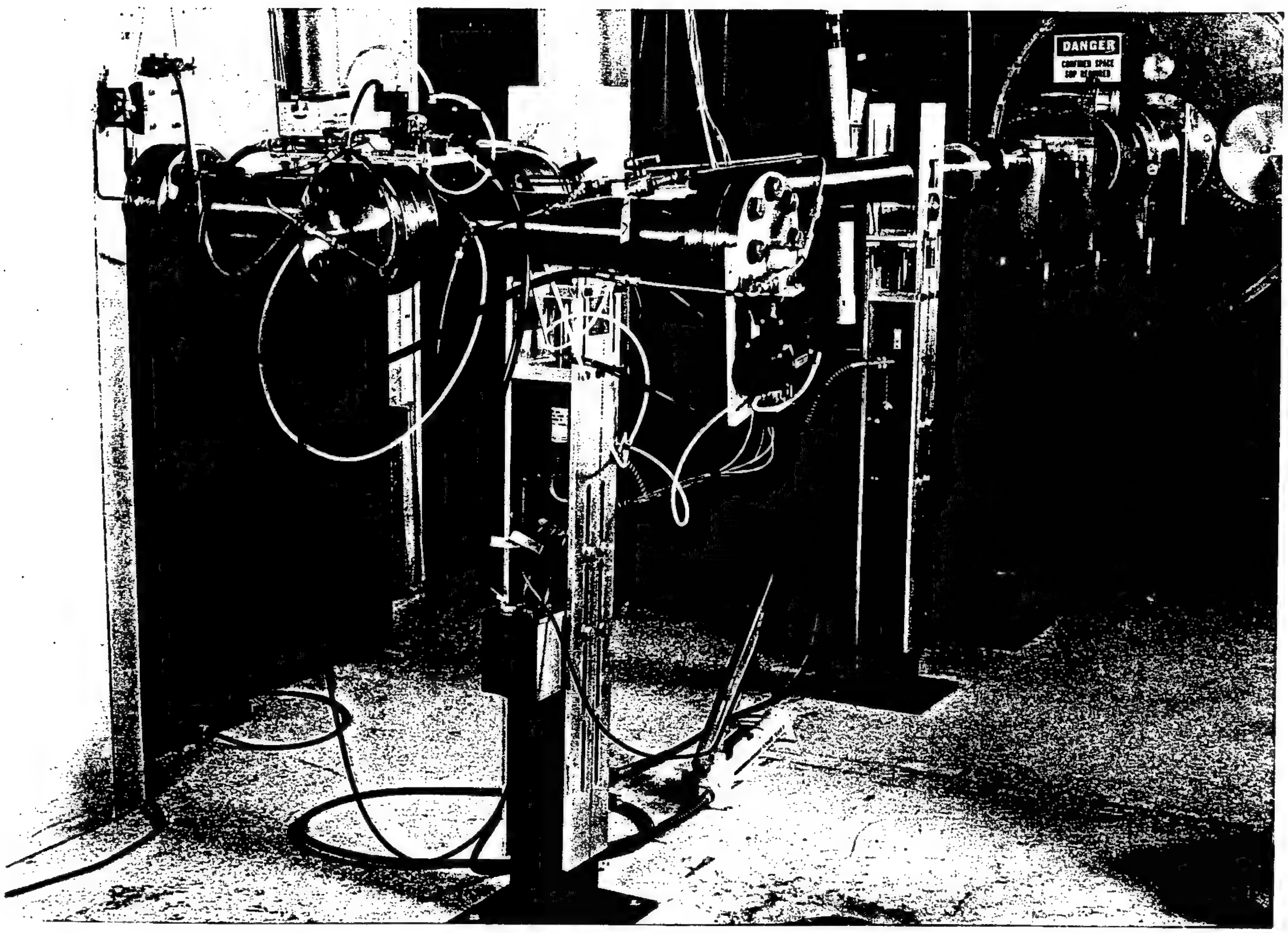

Figure 2.2 Photograph of TIP two stage light gas gun

operation are primarily manual, although the final stages of gas fill are conducted remotely for safety reasons. Turn around time between firing is approximately 1 hour

2.2 SABOT SEPARATION AND GAS ISOLATION

The relative fragility of the glass Verdet probe material, and the square probe cross-section necessitate the use of a sabot to hold the probe during acceleration and make a seal with the circular barrel. LEXAN polycarbonate is used for the sabot, because of its high strength, light weight and machinability. Figure 2.3 shows a schematic of the sabot. The "coke-bottle" geometry and forward placement of the probe minimize disturbance to the probe as the sabot encounters inevitable small irregularities in the barrel. The probe is ground to give a tight (but not press) fit in the sabot, based on tests of probe integrity and alignment vs fit.

Unfortunately, neither polycarbonate nor any other practical sabot material is compatible with the plasma environment, because of rapid ablation and contamination of the plasma. A key element of the TIP system is, therefore, a method of separating the sabot from the probe upstream of the plasma, and prevention of sabot material from entering the plasma. Although sabot-separation methods are commonly employed in ballistics research, projectiles are generally comprised of material much tougher than glass Verdet probes, and are stabilized via one or a combination of means: spin (via barrel rifling), aerodynamically stable shape, or full caliber diameter (vs square, subcaliber Verdet probes). None of these stabilization approaches is practical for the TIP system, and the development of a successful sabot-separation scheme was among the most challenging aspects of the program.

Among several approaches considered and tested, gas-dynamic sabot separation proved to be the only reliable method. As illustrated in Fig. 2.4, passage of the projectile at mach number M through gas at background pressure P_O in the barrel produces a shock wave, raising the pressure on the projectile front face to $P_1 \approx 2P_0M^2$. For a projectile speed of 2 km/sec traveling in nitrogen at 30 psia at 300 K, M≈5.7 and P_1≈1900 psia. If the helium pump gas is vented, the pressure differential will decelerate the sabot, which makes a seal with the barrel wall. The sub-caliber probe is exposed only to P_1, and can slide free from the sabot. Ideally, this method produces no transverse forces during the separation process, so the probe's trajectory and orientation are not affected. An ancillary advantage is that gun gases are partially removed by the vents, reducing muzzle blast.

TIP PROBE/SABOT

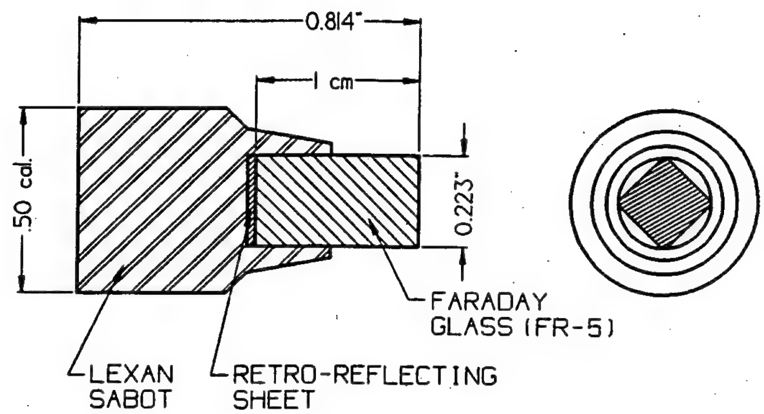

Figure 2.3 Diagram of sabot with faraday probe installed.

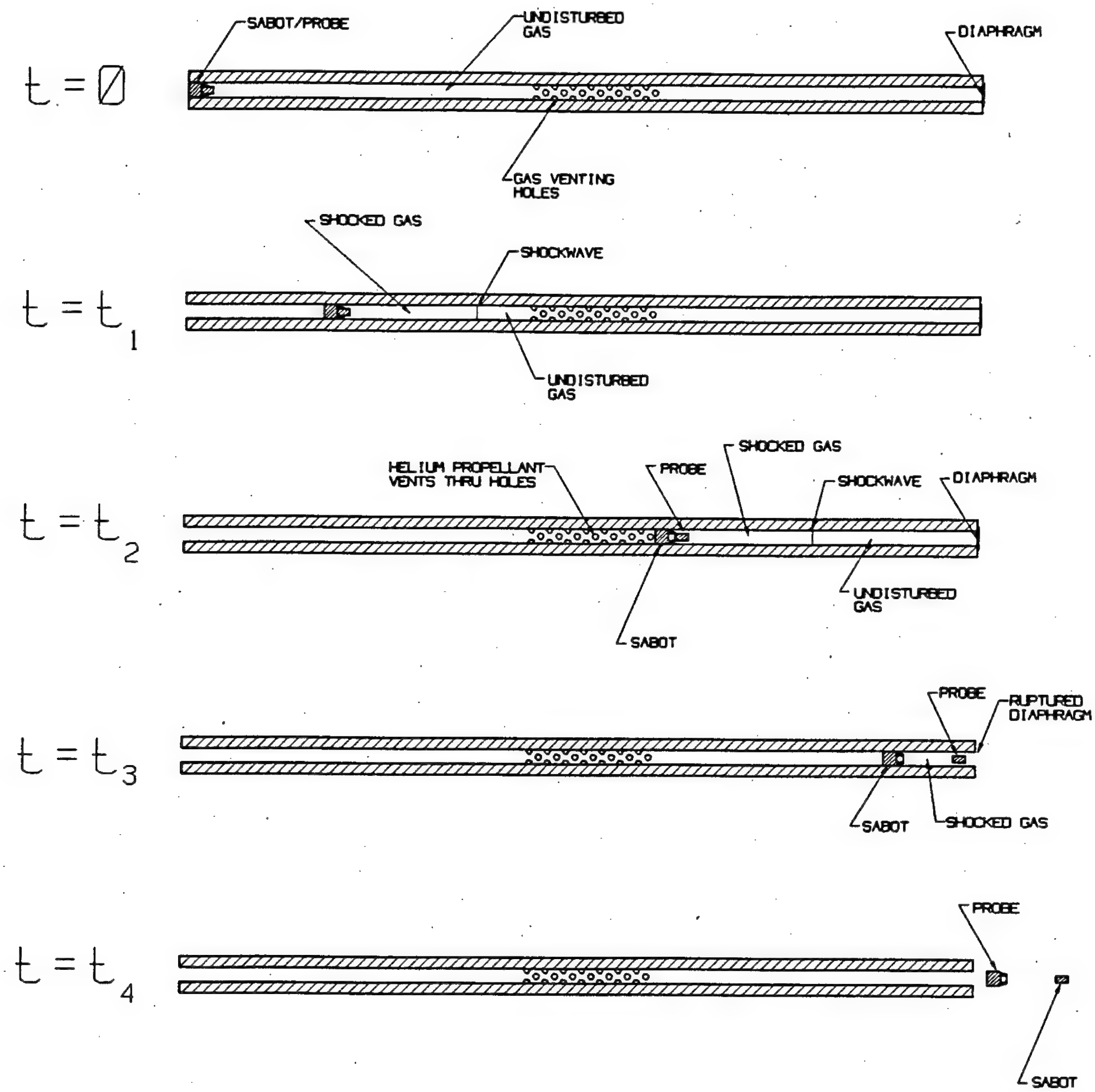

Figure 2.4 Schematic representation of gasdynamic stripping.

Initially, 120 symmetrically placed holes of 3-mm diameter were used for venting, following an accepted "rule of thumb" from previous gas gun experiments that the total vent area should be at least 10 times the barrel cross-section. The sabot-probe separation at a point 0.5 m downstream of the muzzle was measured vs gas fill pressure to determine a suitable operating pressure, as plotted in Fig. 2.5. It is seen that a separation of a few centimeters is achieved at P_0=15-30 psi. However, it was found that in at least half of the shots, rotation of the probe induced during launch was large enough to prevent B-field measurements. It was suspected and verified that the cause was interaction of the vent flow with the separated (and unsupported) probe. The difficulty was largely eliminated by plugging all but 24 of the vent holes with aluminum pins, and operating under conditions that produce a separation distance of 1-2 cm. Under these conditions the probe rotation is acceptably small in 90% of the shots.

The sabot is deflected away from the probe trajectory and the gun gases are dissipated in a 1 m^3 expansion tank placed between the gun and plasma chamber. The tank is pumped to a pressure of $\approx 10^{-6}$ torr and is isolated from the separation gas in the barrel by a 12.5 μm thick, transparent mylar diaphragm affixed to the muzzle. This diaphragm is easily burst by the shock wave ahead of the probe, and does not interfere with probe trajectory. A plate tilted at an angle of 3 ° is placed 0.5 m downstream of the muzzle at a height that allows the probe to pass freely, but deflects the larger sabot at an angle of ≈ 2.8° from the probe trajectory. The deflection plate tilt angle and placement were determined by trial and error to achieve adequate deflection of the sabot, while avoiding sabot disintegration. Fig. 2.6 shows a photograph of the deflected sabot and probe. A catch tube mounted on the downstream face of the expansion tank captures the sabot and confines the detritus of the subsequent sabot disintegration to a minimal cone angle.

While the expansion of gun gases into the tank serves to lower the density, there remains a high-speed cone of gas which could enter the plasma. Two baffles are placed upstream of the deflector to reduce this flow. In addition, the expansion tank is connected to the plasma chamber via a 1.15 m long, 2.5 cm ID tube, which presents a high impedance to gas flow. A high-vacuum, electropneumatic valve is placed in this line, which is opened shortly before a run, and closed following passage of the probe. While this valve serves to maintain isolation of the plasma chamber during pump-down, it is much to slow (closing time of 0.5 sec) to prevent admission of gun gas during a shot.

To prevent this, a high speed "trap door" valve was developed which closes over the tube inlet within 5 msec of probe passage. As illustrated in Fig. 2.7, this valve is

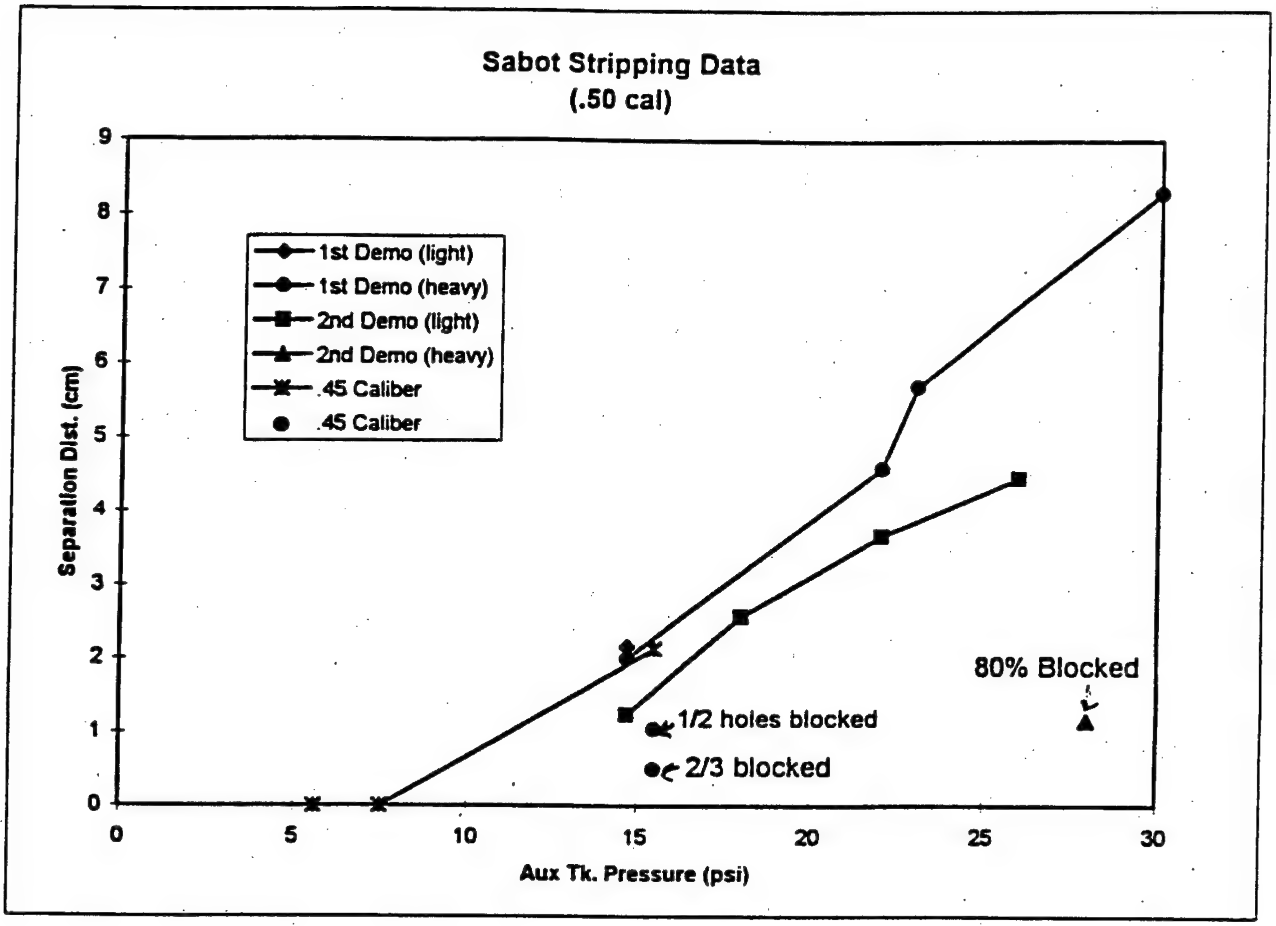

Figure 2.5 Graph of sabot stripping distance as a function of barrel fill pressure for various barrel sizes and stripping configurations.

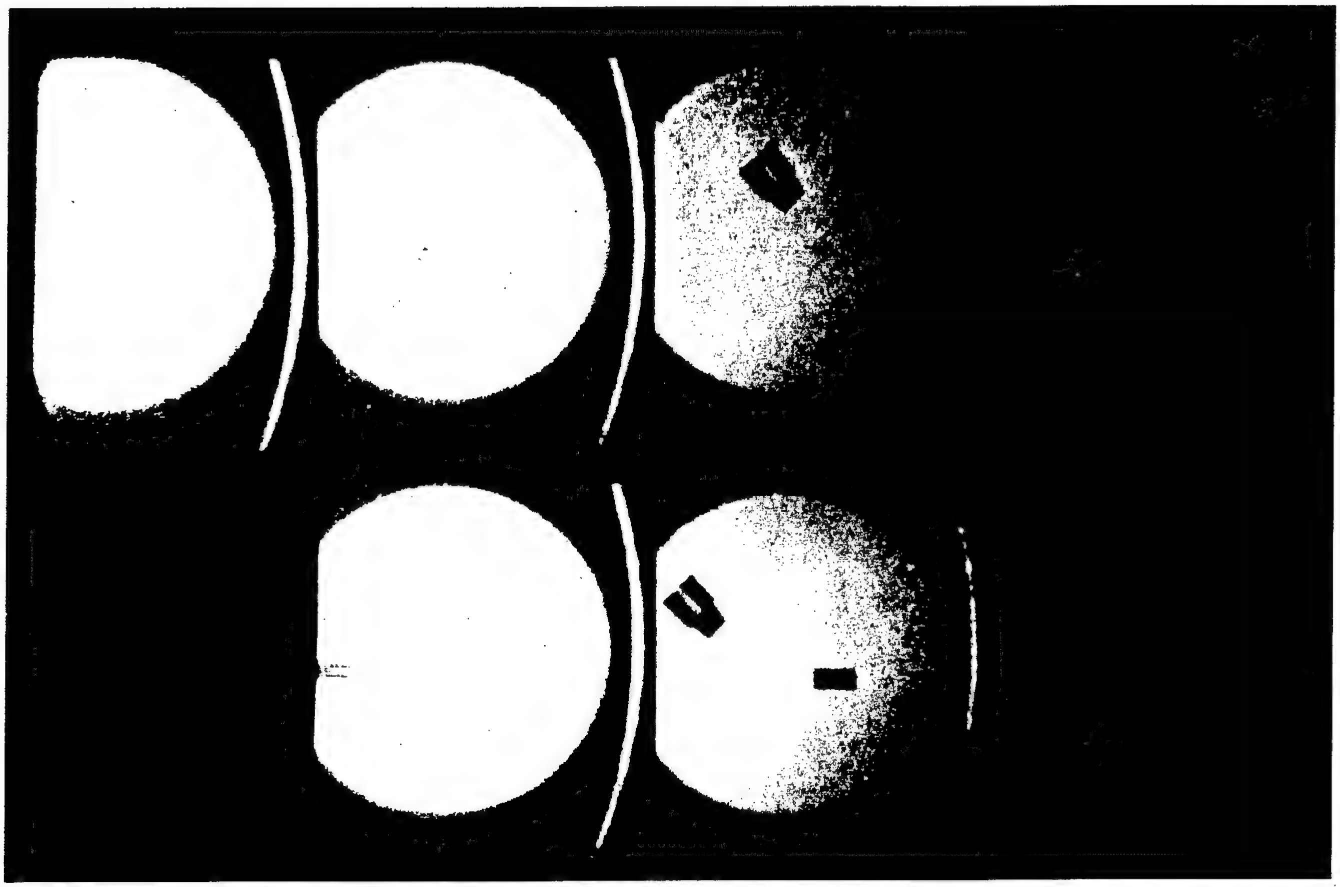

Figure 2.6 Photograph of separated probe and sabot. Objects are traveling approximately two kilometers per second with the photos taken every 10 micro-seconds.

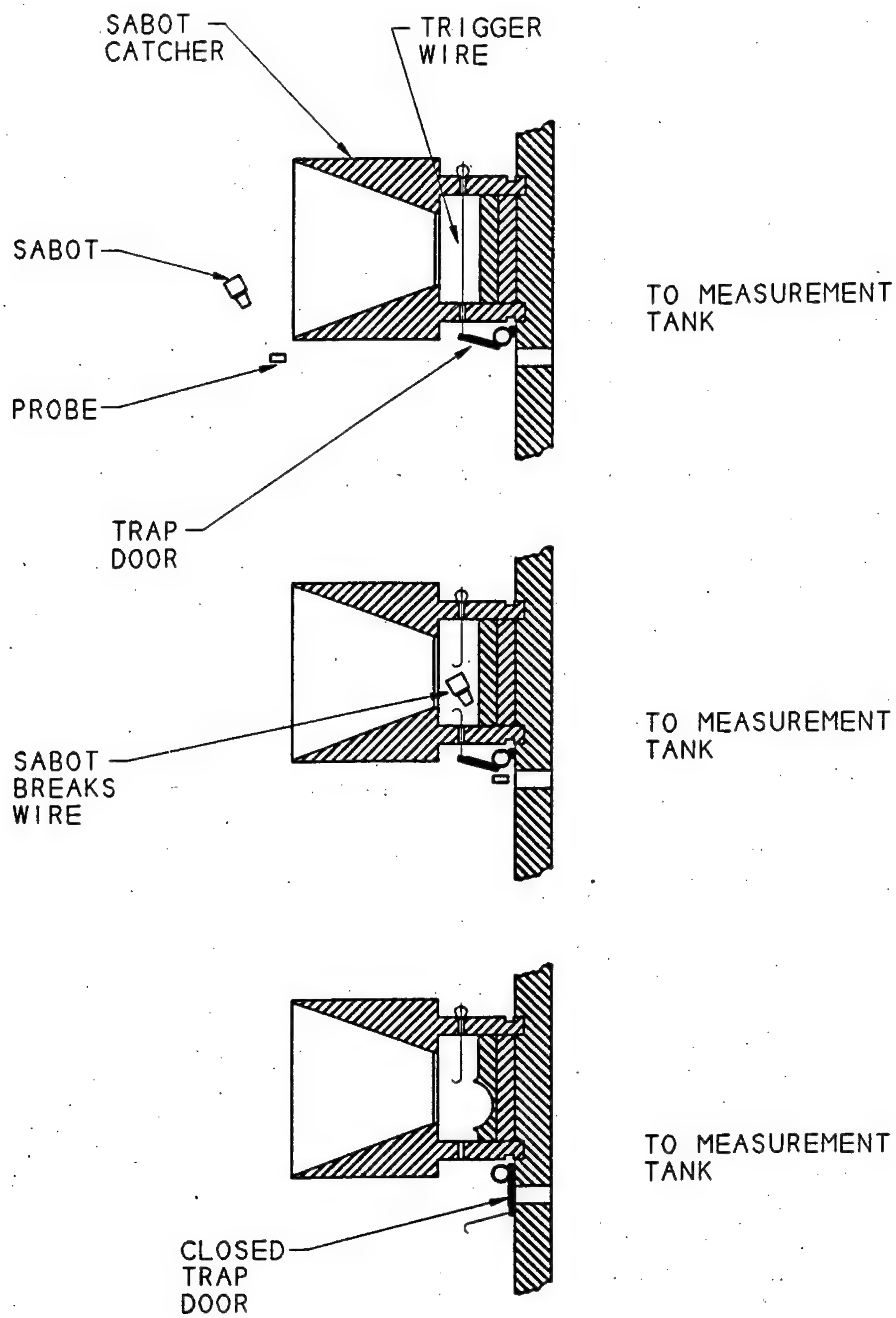

Figure 2.7 Operation of fast-acting trap door valve.

comprised of an aluminum flap tensioned by a spring coil. The flap is held open prior to a shot by a thin steel wire which is attached to the sabot catch tube and crosses the sabot's trajectory. The valve is tripped by the sabot breaking the wire, and the flap closes against an o-ring. Although the valve has performed quite well, the need to open the system to atmosphere between runs to replace the trip wire is a drawback

The above arrangement has proven very effective at minimizing entrance of gun gases into the plasma chamber. The total gas admission was measured to be ≤ 0.4 torr-liter. Operation of the TIP diagnostic on the U.W. HIT plasma, using a sabot only (to eliminate Verdet probe effects on the plasma), showed no significant effects of this gas on the plasma or base pressure. Following passage of the Verdet probe through the plasma chamber, it is captured by a probe catch tube, illustrated in Fig. 2.8. This is isolated from the plasma chamber during pump-down by a second electropneumatic valve. The catch tube also serves to admit the TIP laser beam, and holds a breakable mirror which directs the beam along the probe trajectory. An angled cylinder with a protective inner tube,

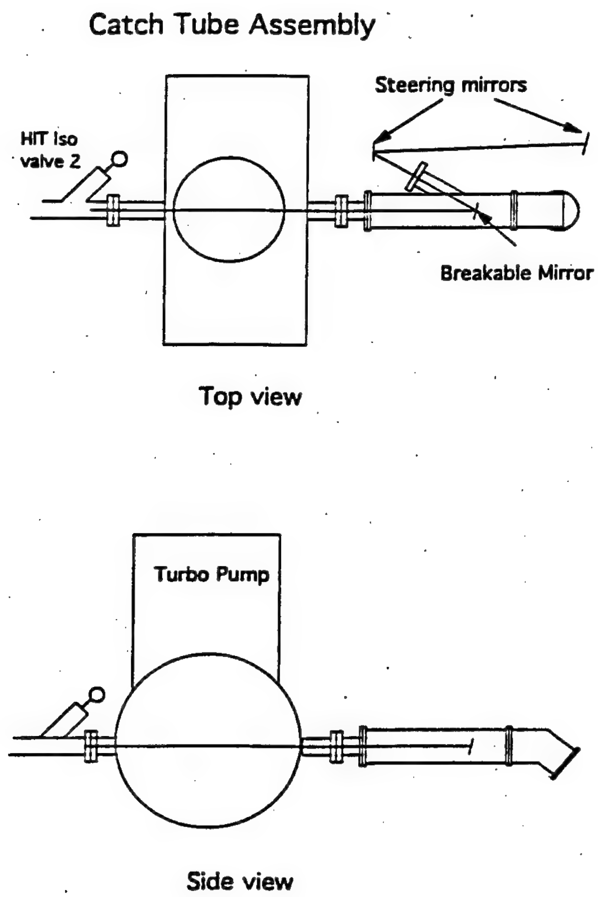

Figure 2.8 Components of the catch tank.

mounted with quick-release o-ring seals, serves to catch debris from probe and mirror disintegration and minimize backscattering of particulates toward the plasma chamber. The catch tube assembly is cleaned between shots (15-minute turn-around), and pumped to a pressure of 10^{-6} torr prior to a shot.

3. VERDET PROBE AND POLARIMETRY

3.1 VERDET PROBE

The Verdet probe is the heart of the diagnostic, serving to rotate the polarization of the illuminating laser beam in proportion to the local magnetic field, and return the light back to the polarimeter. As described in Chapter 1 the sensitivity of the diagnostic is proportional to the probe length and Verdet coefficient, V, of the material. Initially CdMnTe material was considered, owing to its high $V \approx 0.17$ deg/cm-Gauss at a laser wavelength $\lambda = 632$ nm. Tests with this material showed that its high refractive index, birefringence, poor optical quality, and fragility make it unacceptable for TIP. Tb-doped Borosilicate glass proved to be a much superior material in all respects, although the Verdet coefficient is less than 1/10th that of CdTeMn.

Properties of two types of Tb-doped glass probes that have been used are listed in Table 3.1, along with those of CdMnTe. M-32 was preferentially employed, due to its relatively easy optical fabrication and ability to withstand gun acceleration. Also listed in Table 3.1 are properties of Te-Ga-Garnet (TGG), which has a Verdet coefficient 3 times higher at $\lambda = 406$ nm than that of M-32 at $\lambda = 511$ nm. Although tests of garnet "dummy" probes showed that they do not withstand acceleration in the gun, a redesigned sabot and tailored gun-pressure history may allow later use of this material for higher sensitivity.

Table 3.1 Verdet Probe Materials

Company	*Hoya*	*Kigre*	*Litton-Airtron*	*Infrared Tech.*
Material	FR-5*	M-32*	TGG**	CdMnTe**
	Tb-glass	Tb-glass	Tb-garnet	crystal
V (deg/cm-G)	0.00716	0.0095	0.012	0.17
Index n	1.688	1.727	1.967	2.6
Density (g/cm^3)	4.28	4.33	7.26	6.2

A probe length of 10 mm was chosen as a compromise between magnetic field sensitivity and spatial resolution. The cross-section of 4-mm square was chosen to provide an adequate signal strength for the return beam, and yet fit within the 12.5-mm circular probe with adequate support during acceleration. This geometry yields a theoretical sensitivity of 0.0184 deg/Gauss for M-32, i.e., the system should resolve

magnetic field to 16 Gauss given the measured polarimeter resolution of 0.3°. This resolution was demonstrated for static tests, where data-averaging improved S/N. For single-shot measurements, the resolution is governed by noise, and depends on the intensity of the return beam. Typically this noise-dominated resolution was of order 40 Gauss (or ±20 G), although it becomes worse at low return-beam intensities. As described below a new ellipsometer has recently been developed which has a higher S/N and better angle resolution.

The probes are individually calibrated using a precise 2.00956 ± 0.00005 Tesla field of an NMR medical diagnostic at the University. Although the probes are expected to respond linearly to magnetic field strength (only single point calibration needed), this assumption should be further investigated in any future work. Comparisons of measurements spatial variation of the B-field of a static horseshoe magnetic taken with TIP and with a Hall probe did not indicate any non-linearity, but the precision of these measurements was somewhat lower than that used for calibration.

Probe calibration and polarimeter resolution determine the accuracy in measuring local variations in magnetic field. The accuracy in measurement of *absolute* field magnitude depends also on the characteristics of the retroreflector. A retroreflecting sheet material cemented to the back face of the probe has been used for return of the laser beam to the polarimeter. This plastic material, manufactured by Reflexite Corporation, has an array of micro-corner cubes embedded in it. Although it preserves polarization much better than a single corner cube, some polarization rotation and generation of ellipticity is observed, dependent on the orientation of the sheet with respect to input polarization. At normal incidence the peak-to-peak variation in return beam polarization as the probe rotates about its axis is ≈ 1°, corresponding to a fictitious B-field of ~ 50 Gauss. At inclined angles of incidence the shift in polarization angle ranges up to several degrees.

Despite the good resolution of the system for local field variations, the uncertainty in (time varying) probe orientation during transit through a plasma, reduces the accuracy in determination of the absolute field magnitude. Based on comparisons between Hall probe data and TIP data on the background (vacuum) field on the HIT plasma machine, the absolute accuracy is of order ± 200 G with the present retroreflector. For this reason, because the built-in divergence of the return light lowers the signal at the polarimeter, and because of the relatively short survival time of the material in a plasma, future efforts shou concentrate on development of alternative retroreflection methods.

An Ar-ion laser of nominal power 1 W was used for probe illumination. The laser was tuned to the 514 nm line. Although the Verdet coefficient for the Tb-doped glasses is

higher at the strong 488 nm laser line, absorption in the glass at this wavelength precludes its use.

3.2 POLARIMETRY

The polarimeter used during most of the program and for the initial experiments on HIT was developed early on in the program, and is described in detail in Ref. 9. Briefly, the return beam is split into 3 beams, each passing through a polarizer, laser line filter and focusing lens into a Si photodetector/amplifier. The polarizers are oriented 60° apart, which allows the sensitivity of the system to be nearly independent of polarization angle. The system is calibrated by recording the detectors' response vs known input polarization, and this calibration data is used for determining magnetic field when reducing data from a shot. As noted above, the angular resolution of the polarimeter is about 0.3° for repetitive sampling, and about 1° for a single shot, limited by noise. A major drawback of this system is its inability to distinguish between polarized light emanating from the Verdet probe and scattered light. The latter generally has a different dependence on probe position from the former, which introduces some uncertainty in the determination of magnetic field. A manifestation of this is the apparent shift in baseline polarization at zero field as the probe passes from upstream of the plasma chamber to downstream.

During the latter part of this program, an ellipsometer was constructed to improve the sensitivity and resolution and to provide a method for distinguishing polarized and unpolarized light. An ellipsometer is also a required element for the use of a transverse-field probe described in Section XXX. In this system the return light is split into 4 beams, three of which are analyzed as above, and the 4th beam passes through a quarter-wave plate, an analyzer oriented at 45° from the wave plate's principal axis, and into detector 4. From the four detector signals one can extract the polarization and ellipticity of the polarized component of return light, and the fraction of the return light that is polarized. In addition, each detector/amplifier system has a S/N about 4 times higher than that of the original polarimeter, and the optics are designed to introduce lower ellipticity. The resolution is about 0.03° (magnetic field resolution of ~ 2 G), and the noise-limited resolution for a single shot is ~ 20 G (or ± 10 G). As noted above, the absolute accuracy of the system is limited by retroreflector characteristics, not the polarimetry, per se.

4. VERIFICATION OF DIAGNOSTIC WITH FIXED MAGNETIC FIELD

To demonstrate the ability to accurately measure a the spatial distribution of a magnetic field using a high-speed Verdet probe, and to prepare for field measurements in a plasma, the TIP probe was launched through a permanent magnetic field inside a vacuum vessel (simulated plasma chamber). This test also served to demonstrate the effectiveness of the gas-isolation system, and to measure the timing and reliability of the diagnostic.[14]

The layout for the demonstration experiment shots is shown in Fig. 4.1. The gas isolation system is set up as described above, using an expansion tank isolated from the gun by the mylar diaphragm, and from the 0.025 m^3 test chamber by the isolation valves and trap-door valve. A ~ 2 kG permanent magnet was mounted in the test chamber. Base pressure for the vacuum tanks was typically 3 x 10^{-6} torr.

Figure 4.2 shows the signals received on the three detectors for a typical shot. The data was taken at a rate of 1 MHz using a CAMAC 6810 digitizer. Initial polarization of the laser was nearly parallel to the transmission axis of detector 2. Modulation of the signals due to the magnetic field is clearly seen. The overall increase in intensity is due to the probe getting closer to the collecting optics of the detection system. Figure 4.3 shows the detector signals normalized by their sum. This data is fit to the optical detection system calibration curves in order to determine the polarization angle of the reflected light and the local magnetic field.

Figure 4.4 shows the magnetic field profile measured using the TIP diagnostic. Plotted along with the TIP data are measurements taken with a Hall probe along the flight path of the probe. The two diagnostics, one using a Verdet probe traveling at 2.0 km/sec, and one using a static Hall probe, agree to within ≈ 40 Gauss. This difference owes in part to uncertainty in the exact chord of the Verdet probe, and in part to the large field gradients. As noted above, a static calibration of the polarimeter showed it to have a resolution of 0.3°, corresponding to a magnetic field resolution of ≈16 G.

Compatibility with the high vacuum environment of a plasma experiment was evaluated by measuring the amount of muzzle gas entering the simulated plasma chamber. This was determined by recording the pressure rise in the chamber using a fast response baratron gauge. The typical pressure rise was 7 mtorr. The volume of the tank and associated connections was about 50 liters, indicating an admission of less the 0.4 torr-liter of helium into the plasma chamber. The base vacuum remained acceptable over many shots with minimal maintenance required.

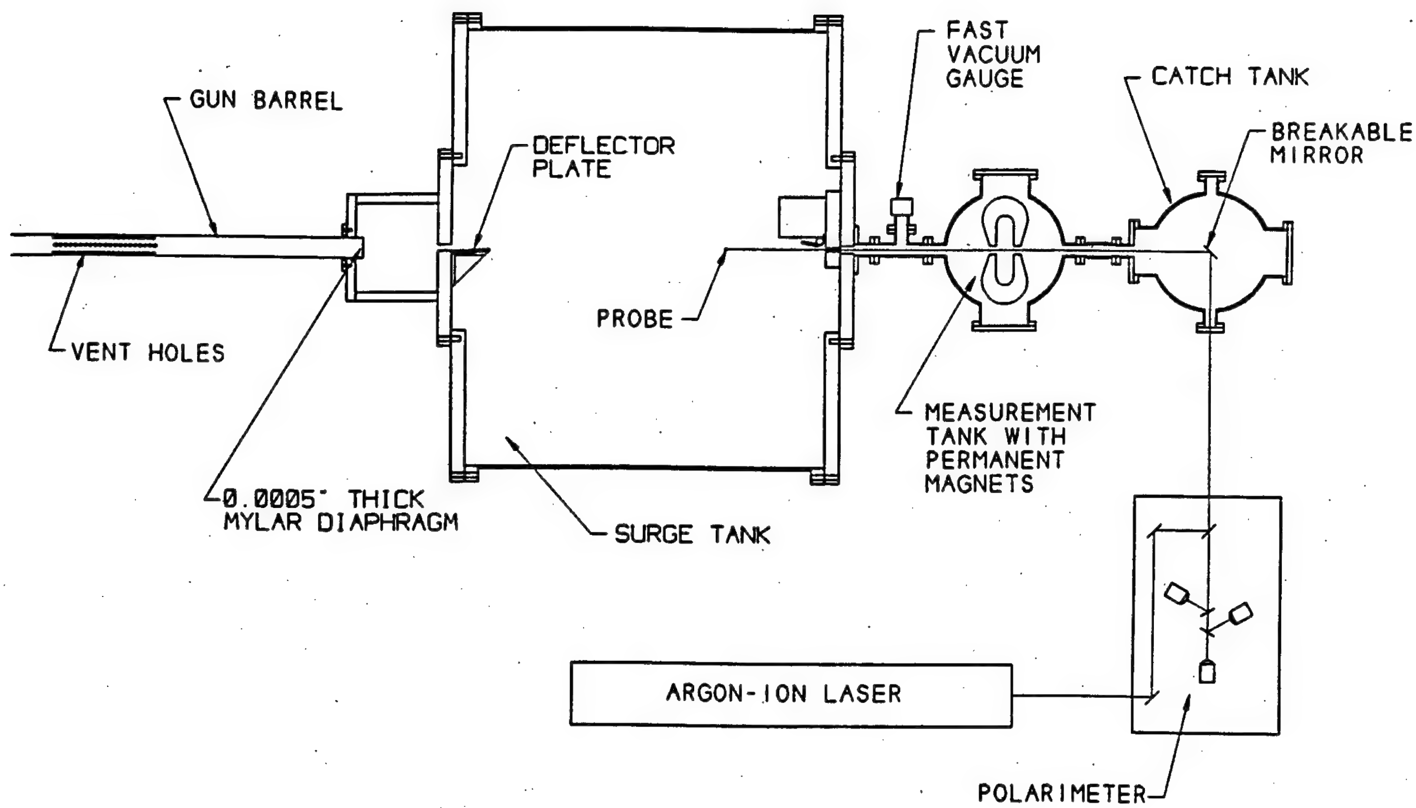

Figure 4.1 Diagnostic layout for demonstration experiment to measure a static magnetic field using a 2 km/sec TIP probe.

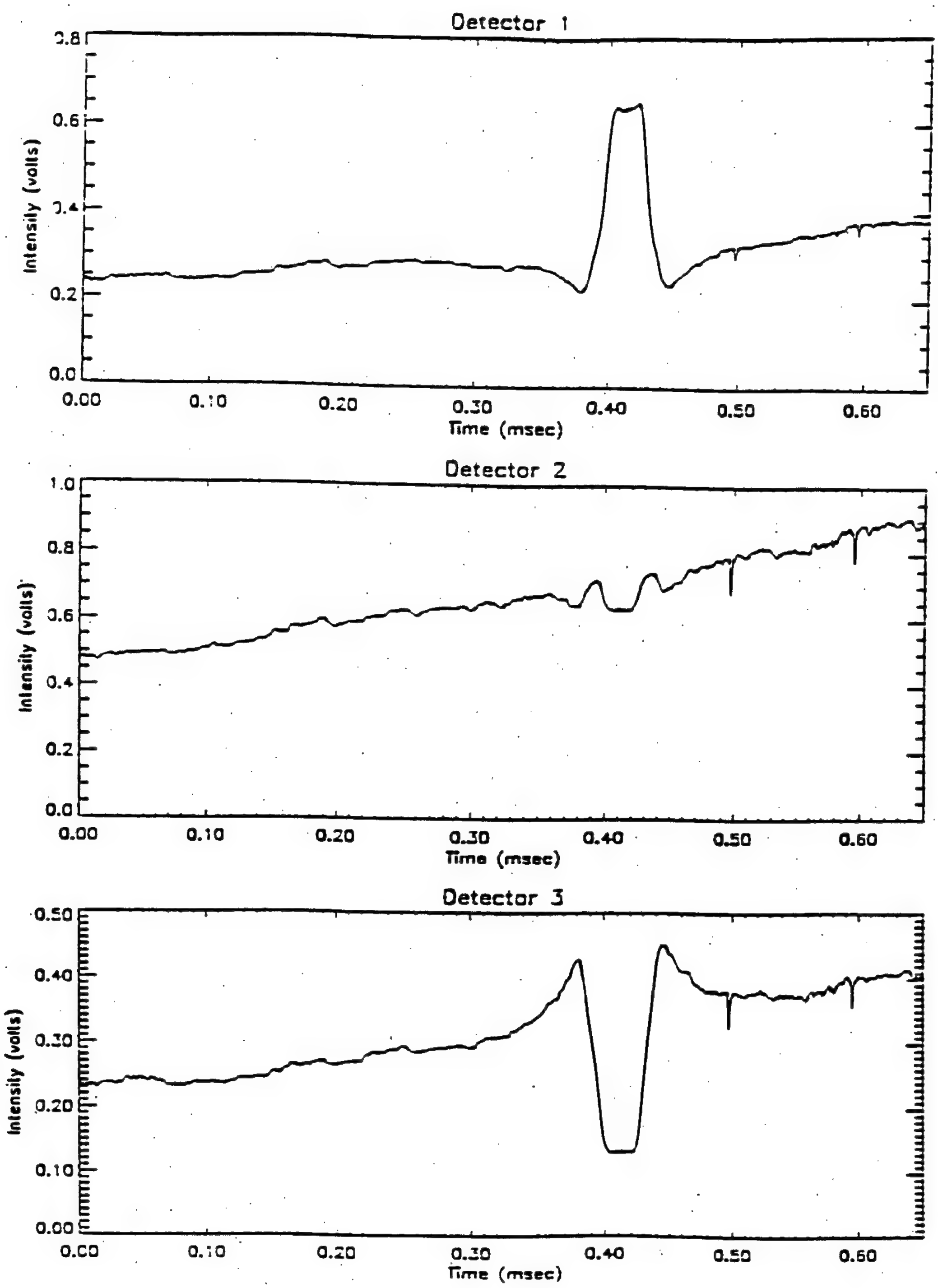

Figure 4.2 Raw signals recorded from detectors for high-speed TIP measurement of permanent magnetic fields.

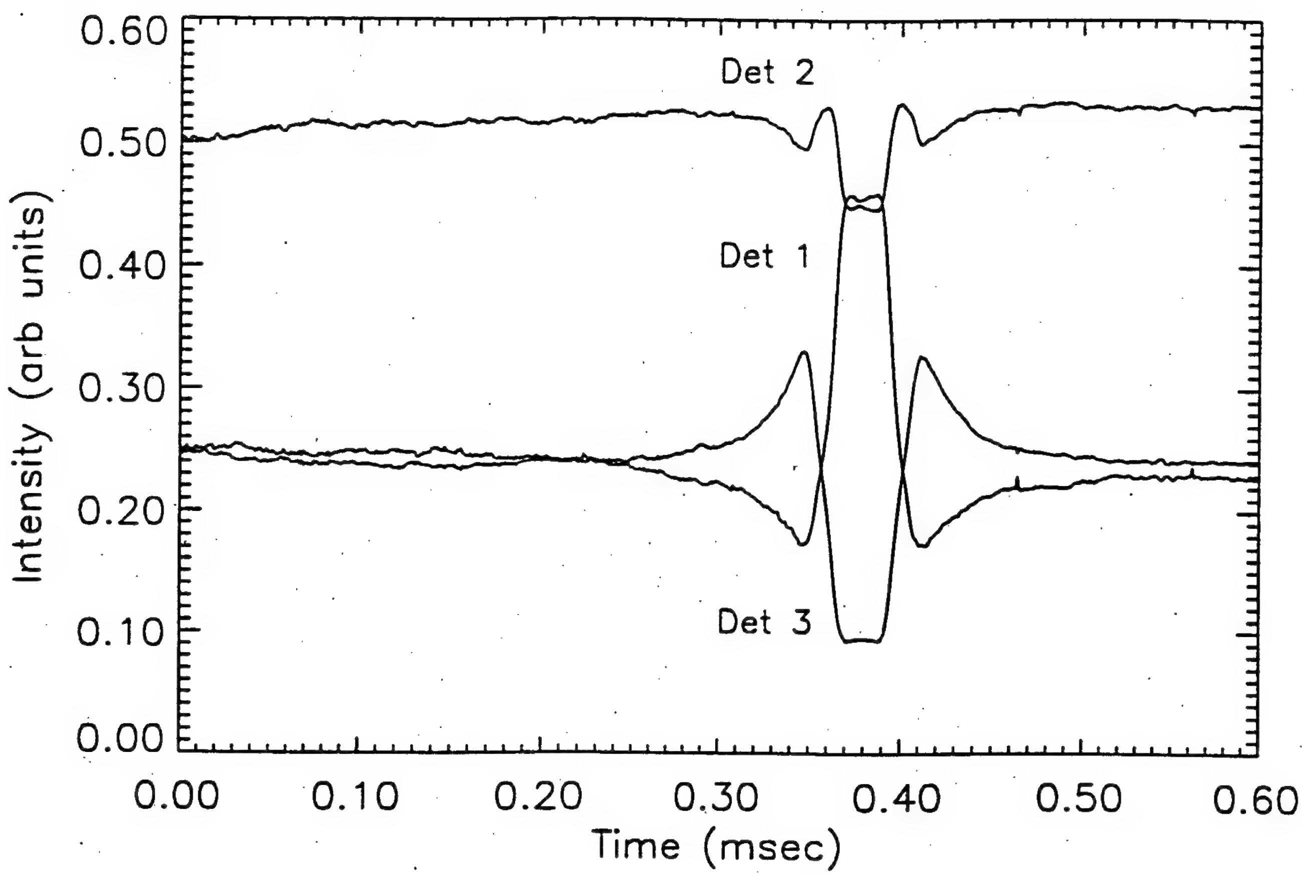

Figure 4.3 Normalized signals for high-speed TIP measurement of permanent magnetic fields.

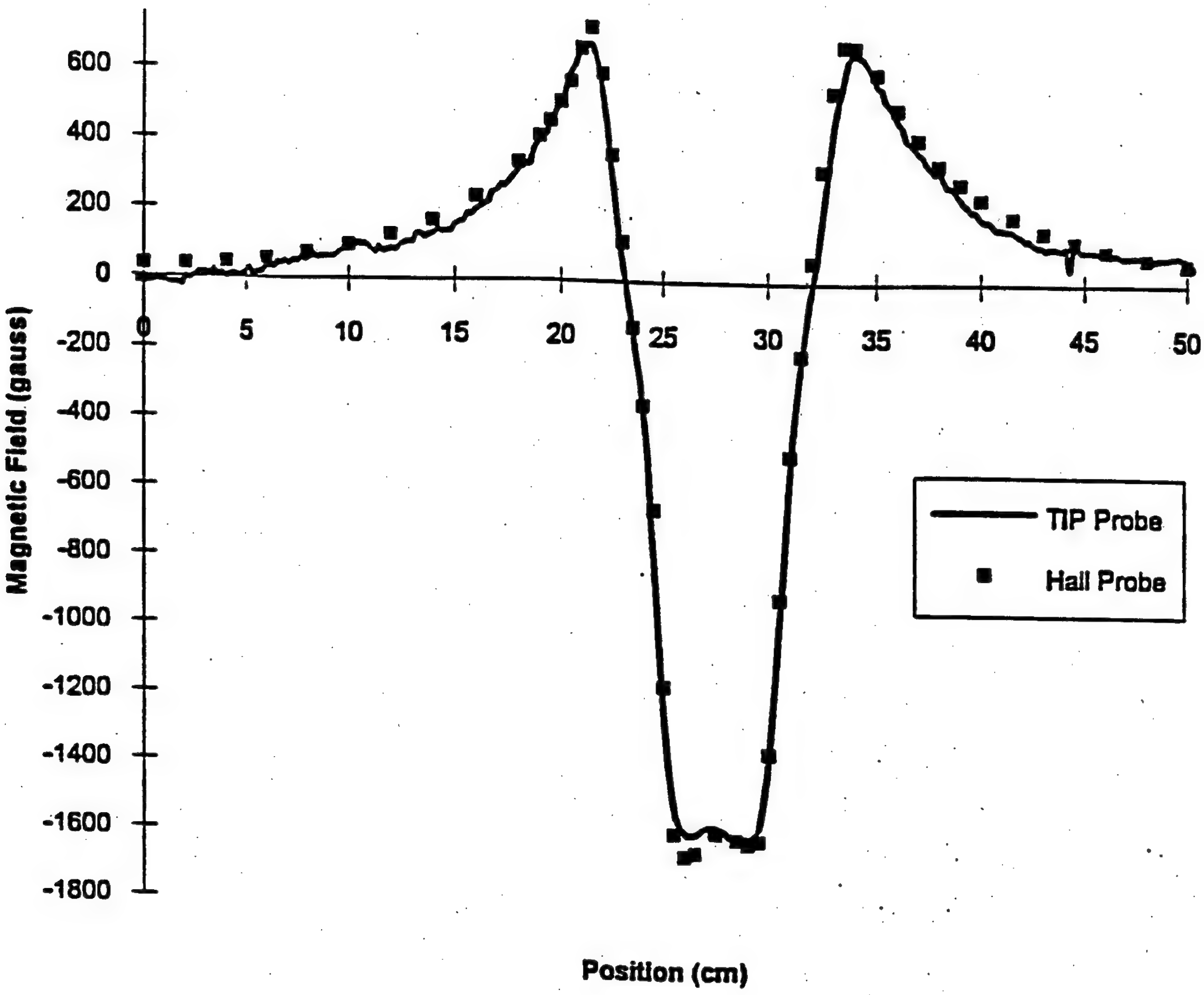

Figure 4.4 Permanent magnetic field profile measured by TIP probe at 2 km/sec compared with Hall probe measurements of the field.

5. MAGNETIC FIELD MEASUREMENTS ON THE HELICITY INJECTED TOKOMAK

5.1 RESULTS OF FIELD MEASUREMENTS

Several successful measurements of the internal magnetic field profile of the Helicity Injected Tokamak[18] were conducted using the TIP diagnostic.[5,6] The purpose of these measurements was twofold. First, they were used to evaluate and test the ability of the TIP diagnostic to make measurements in a hot plasma and second, they were used to investigate the internal toroidal magnetic structure of HIT.

Figure 5.1 shows the layout of the TIP diagnostic mounted on HIT. The total flight path length was approximately 4.5 meters, with 1 meter of travel in the plasma. Figure 5.2 shows a side view of the probe path through the tokamak. The magnetic profile measured by the probe is significantly affected by the close proximity to the toroidal field return bundles. By fitting the measured data to the characteristic fields created by the bundles outside the plasma, along with the fields created by some permanent magnets intentionally placed opposite each other across the probe path the trajectory and attitude of the probe can be determined.

Figure 5.3 shows the raw signal data received during a shot through the plasma in which the ellipsometer optical detection system was used. The modulation of the return bundles is clearly seen in two smaller peaks flanking the large modulation in the center due to the large toroidal field. The overall signal intensity decreases towards the end of the traverse and this reduces measurement accuracy in this region. The magnetic field profile obtained from this data is shown in Fig. 5.4a with the vertical lines indicating the region in which the probe was inside the copper flux conserving boundary of the tokamak. Plotted with this measured data is the calculated vacuum magnetic field based on the currents measured in the toroidal field coils themselves. This calculated field was verified to 20 G accuracy using Hall probe measurements (no plasma present).

Figure 5.4b shows the residual difference between the field profile measured by the TIP diagnostic and the calculated vacuum field. To first order, the measurement follows the vacuum magnetic field as expected. Part of the residual is due to the plasma, but systematic uncertainties in the measurement precluded a precise determination of the equilibrium toroidal field and plasma current distribution. This would have required an absolute accuracy of $\approx$ 20 Gauss throughout the measurement. The probe's response to *local* field variations remains quite accurate, and yielded very significant results for plasma mode structure.

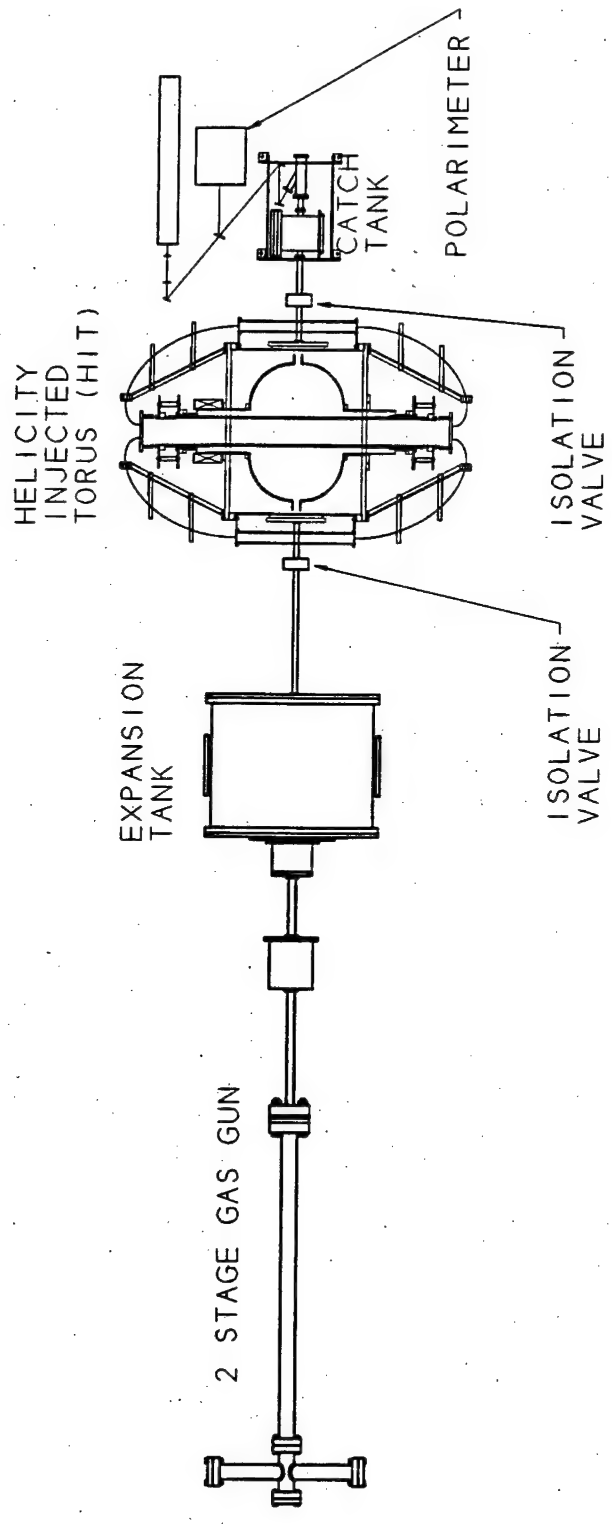

Figure 5.1 Diagnostic layout for TIP measurements on the HIT plasma facility.

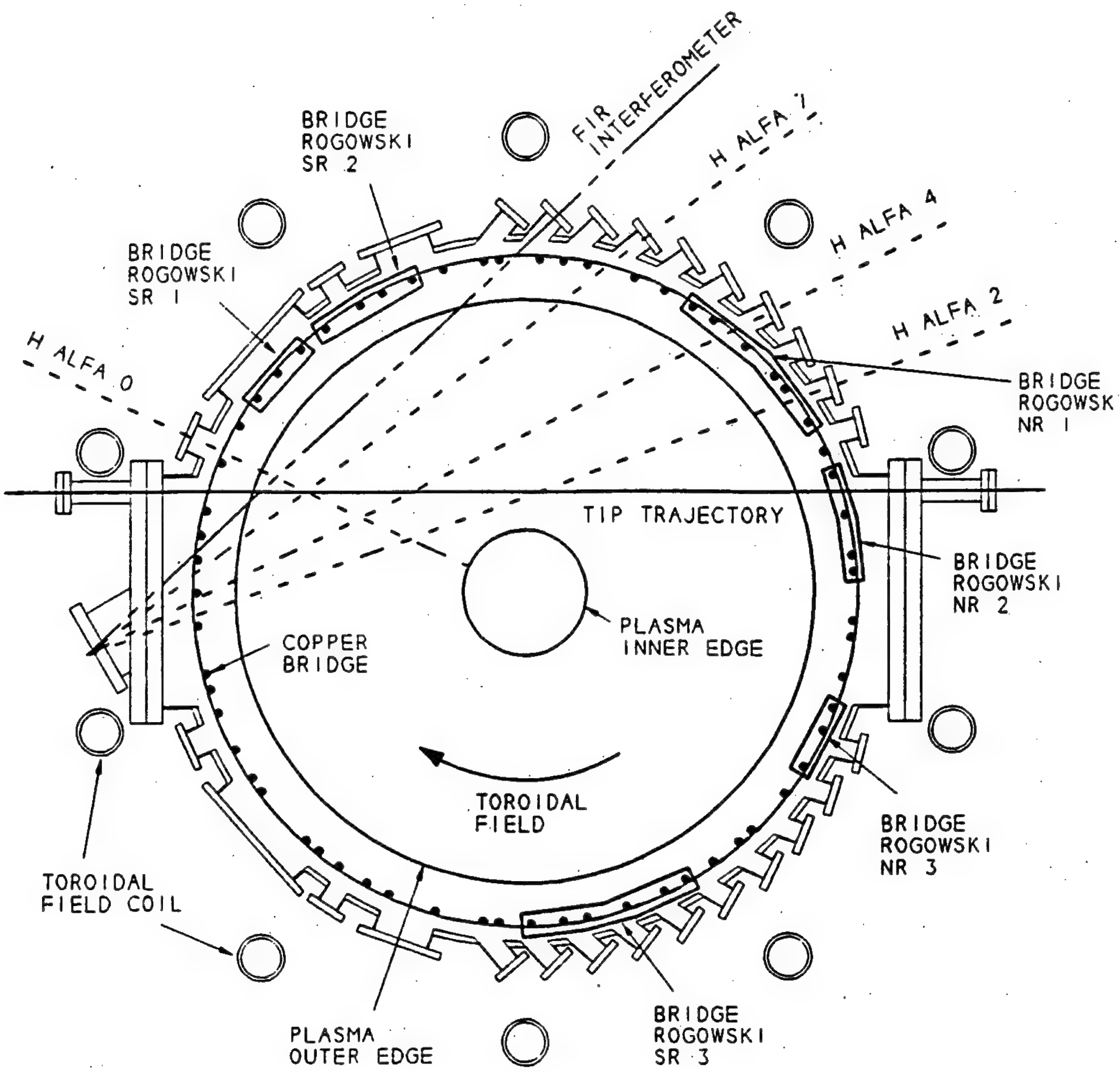

Figure 5.2 Diagram of TIP probe trajectory through HIT tokomak.

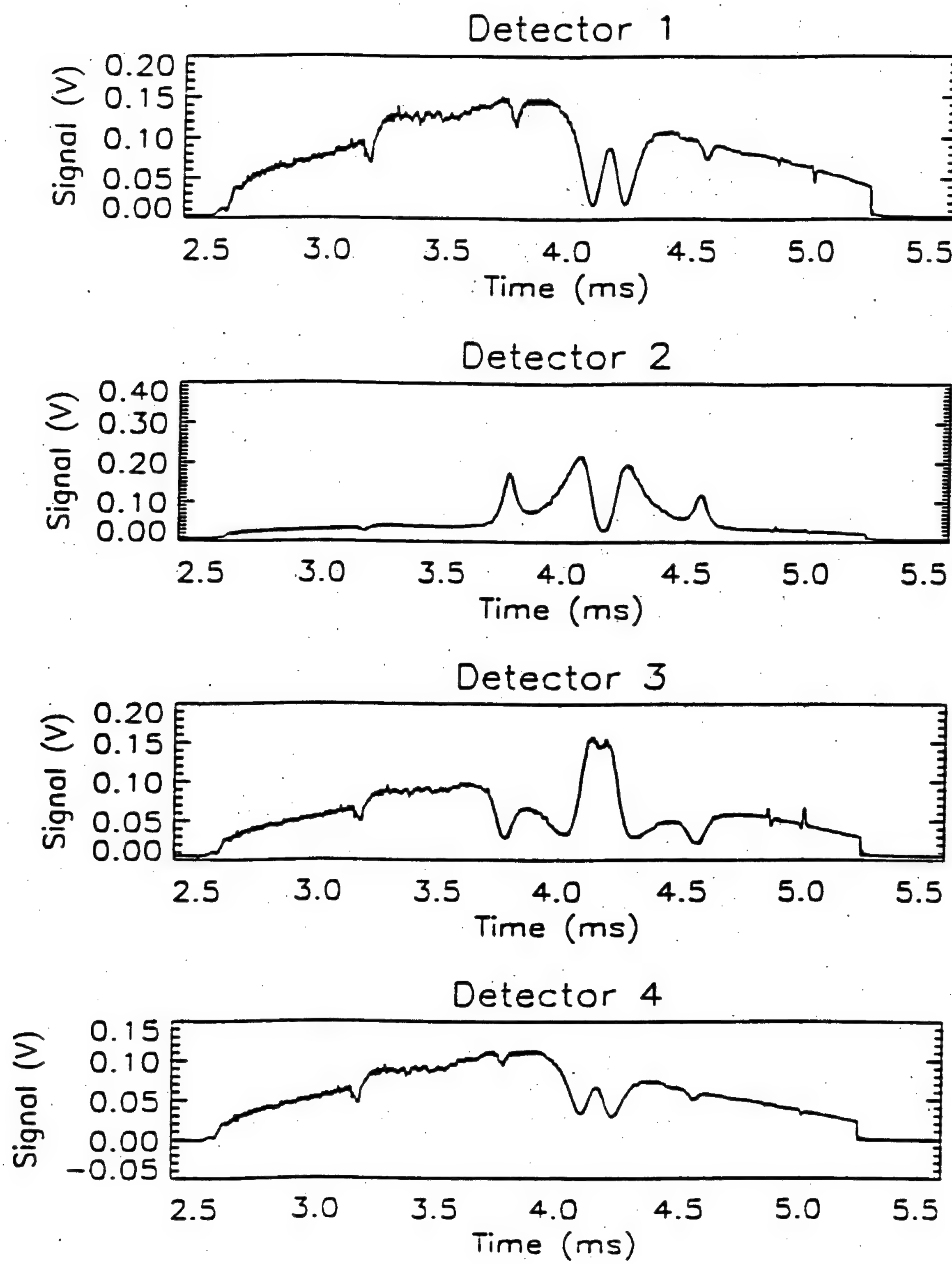

Figure 5.3 Raw detector signals from TIP ellipsometer during a shot on HIT.

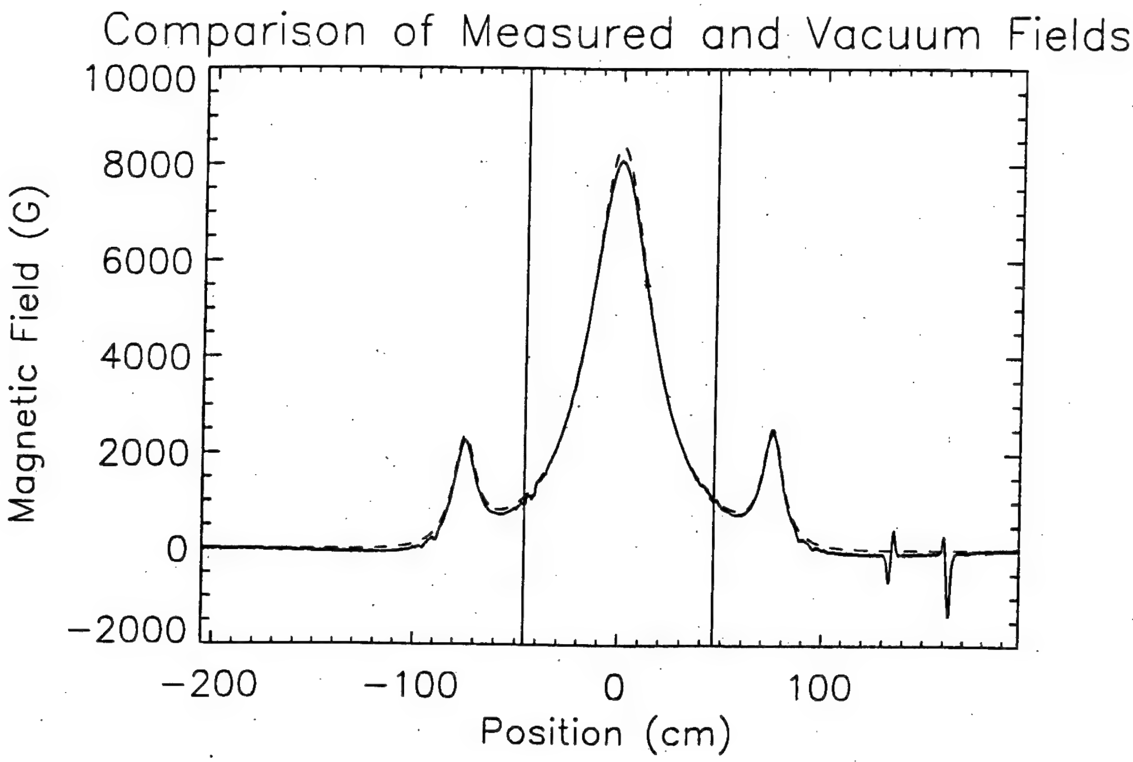

Figure 5.4a Toroidal magnetic field profile on HIT plasma measured by TIP diagnostic (solid line), and calculated vacuum field (dashed line).

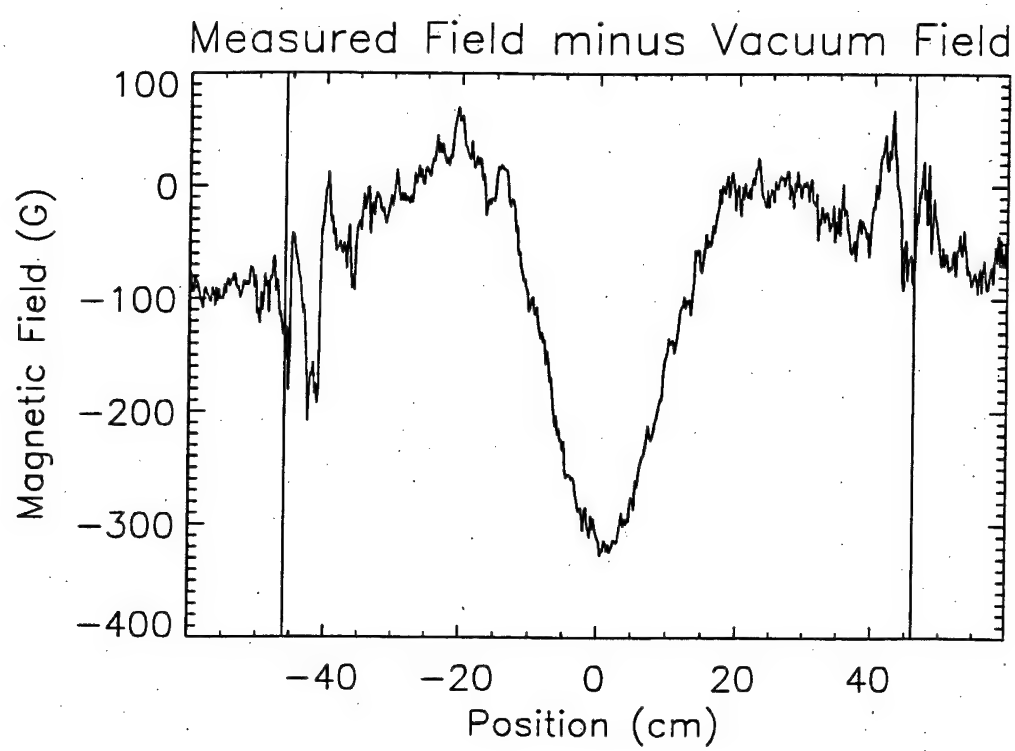

Figure 5.4b Residual magnetic field profile (measured plasma field minus calculated vacuum field). n=1 plasma oscillations are seen near plasma edge. Vertical lines mark flux conserving boundary.

The 100-200 gauss oscillations observed near the flux conserver as the probe enters and exits the plasma are due to a rotating n=1 oscillation mode. The presence of this mode had been observed with surface probes previously, but the magnitude and spatial extent of the mode was unknown. Figure 5.5 shows the correlation between the TIP measurement and a local measurement of current in the flux conserver near the probe's exit location. Note the probe is in phase with the current probe measurement when the TIP probe is near the current probe at the exit point, and 180° out of phase at the entrance point located opposite the current probe location, thus confirming the mode is n=1. The measurement of this mode is significant in two ways. First it demonstrates the ability of the TIP diagnostic to spatially measure a 100 to 200 gauss oscillation in the presence of a large background field. Second, it provides important physical insight into the n=1 mode which is considered a candidate mechanism to explain relaxation and current drive in the Helicity Injected Tokamak.

The TIP measurements on the Helicity Injected Tokamak were found to have an accuracy in absolute magnetic field of about ±200 gauss or ±2.5% of the measured values. The accuracy in measuring local variations is estimated to be ≈20 gauss. This is a high field resolution for any plasma diagnostic, and is significantly better than any existing techniques used to measure magnetic fields inside plasmas. However, the systematic uncertainty is presently too great to make a full determination of the internal current profile by measuring the toroidal field profile. The diagnostic has demonstrated the bandwidth and spatial resolution sufficient to measure the internal mode oscillations to a high degree of accuracy, and implementation of the further should allow precise measurement of the overall equilibrium field profiles.

5.2 PROBE EFFECT ON THE PLASMA

Interaction of the plasma with the probe results in the introduction of impurities through the process of sputtering and ablation. The effect of these impurities was qualitatively investigated by observing various plasma diagnostics as the probe transited the plasma. The Verdet probes used for measurements on HIT were unclad, since the heat flux computations discussed in Chapter 1 indicated that a "bare" glass probe should survive the ≈ 0.5 msec exposure to the plasma. The retroreflector material is susceptible to ablation over this exposure duration, and initially a 100 μm shim of stainless steel was cemented to the back side of the retroreflector to prevent this. However, it was found that in many of the shots, the steel shim and retroreflector tore away during acceleration,

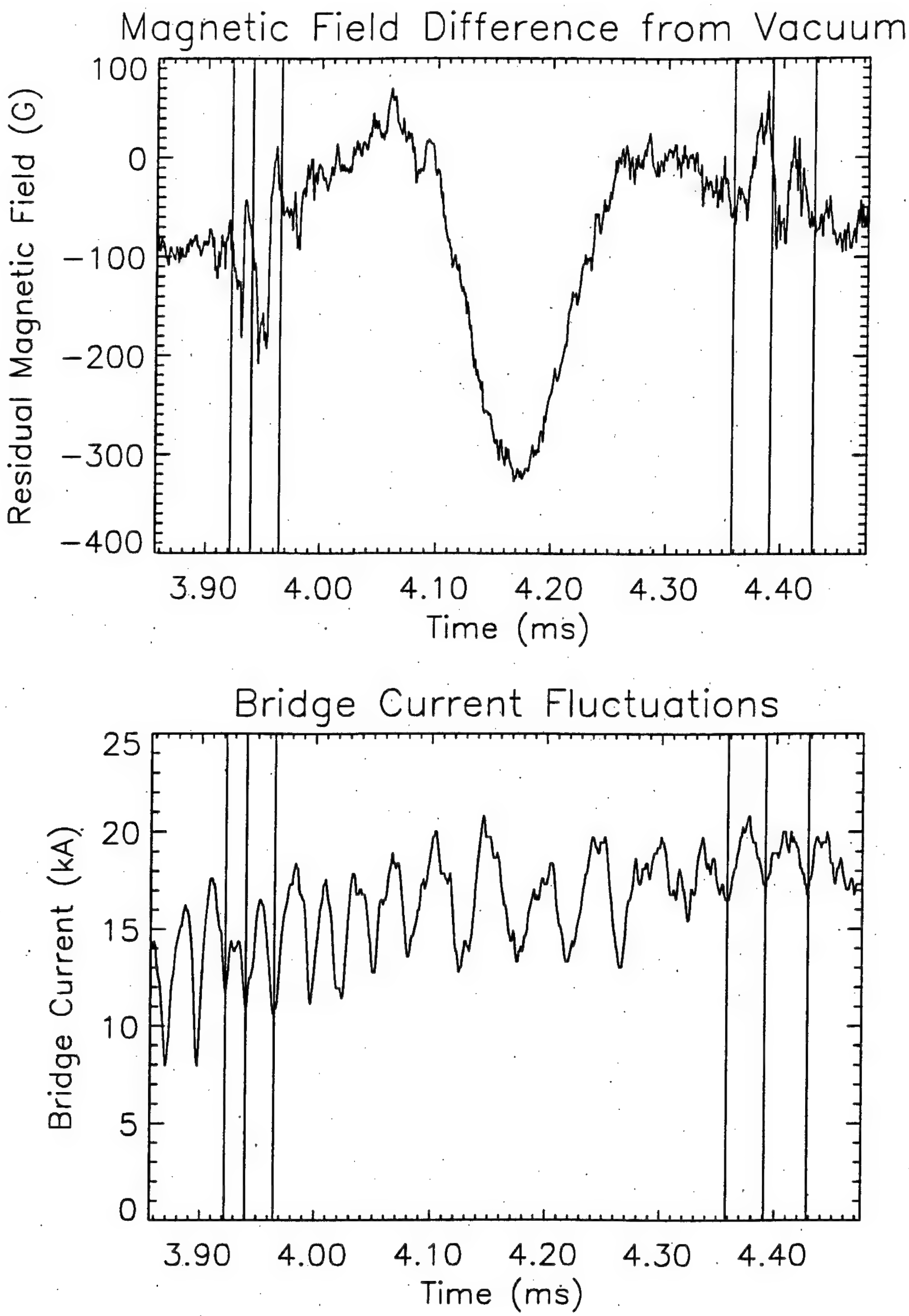

Figure 5.5 Correlation between n=1 oscillations measured using TIP (top) and surface current measurements (bottom). Vertical lines denote relative phasing of oscillations measured by the two diagnostics. Note that current measurements are made near probe exit (TIP signal at ≈ 4.4 ms).

disabling the probe. Thus, in the shots taken for field measurements, the shim was not used.

Data from a typical plasma shot is shown in figure 5.6, portraying the plasma current and plasma density. Again the vertical lines show the time period in which the probe was in the plasma. Perturbation to the plasma was minimal during the first 200 μsec of probe presence in the plasma. After this time, a drop in plasma current is observed, likely due to ablation of the retroreflector material. Density measurements using Far Infrared Interferometry showed no probe effects.

In shots where a retroreflector was not attached to the probe, no drop in the current is observed, as shown in figure 5.7. This consistent with the conservative ablation time predictions made by the heat flux models which showed the bare glass probe to be near the point of ablation assuming the plasma was in the range of 40-80 eV. By coating retroreflector material the adverse effects of the ablated retro-sheet can be avoided.

Finally, a shot was taken in which only a sabot was launched without a probe. This was done to determine if the small amount of Helium driver gas allowed to escape the expansion tank was affecting the plasma. No evidence of the presence of this gas was observed in any of the measured plasma parameters.

One other concern for the TIP diagnostic was its effect on the tokamak base pressure which routinely operated between 8×10^{-9} and 3×10^{-8} torr. Alignment of the TIP diagnostic requires open connection between the tokamak and the TIP vacuum systems for periods up to several minutes. These periods were found to have little effect on tokamak base pressure, raising it a few 10^{-8} torr and immediately following isolation base pressure was re-established. The content of the impurities was investigated with a residual gas analyzer before and after several TIP shots. The results showed no significant changes in long term baseline impurities. Overall, performance of the tokamak was not diminished as a result of TIP operation.

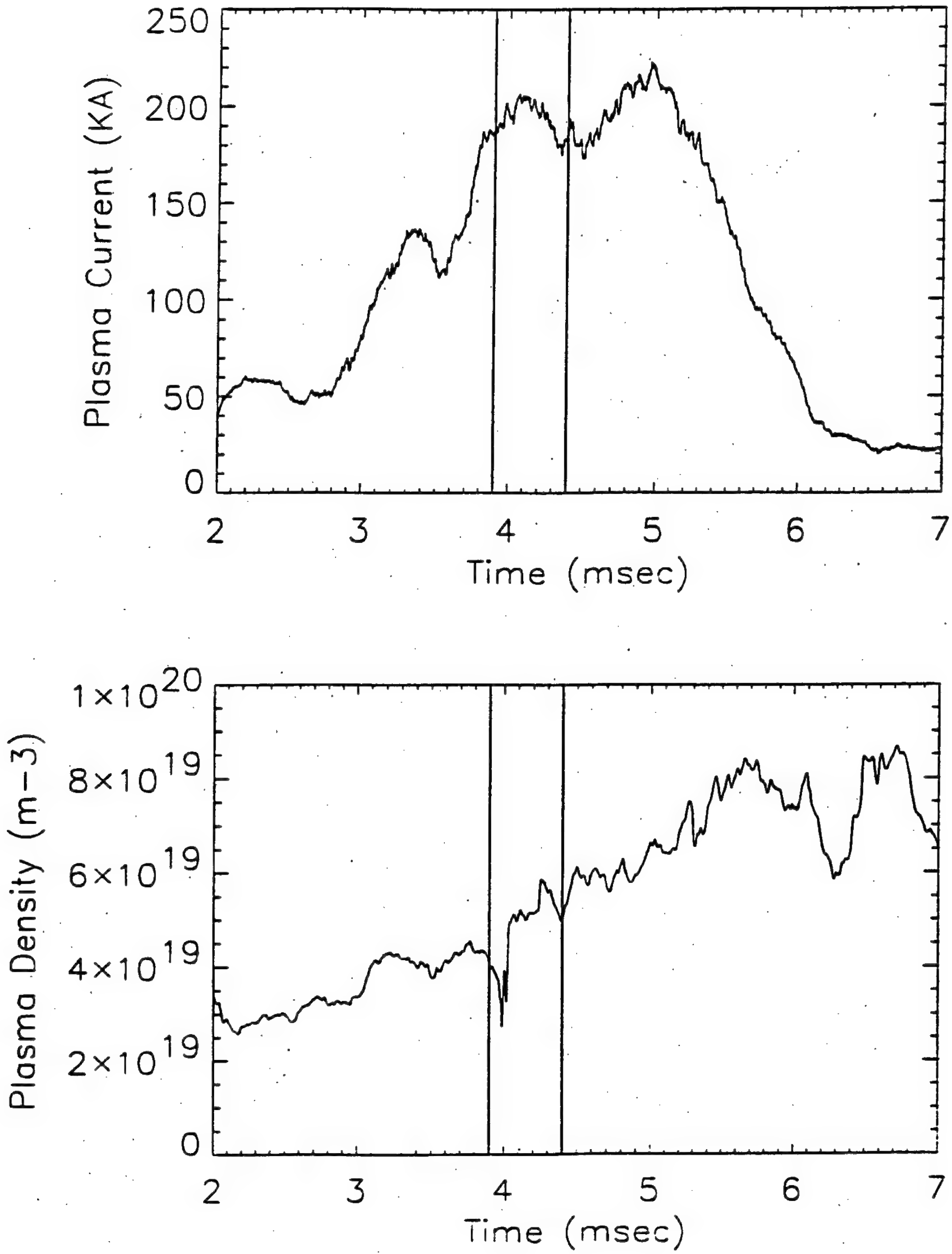

Figure 5.6 Plasma current (top) and density (bottom) versus time.

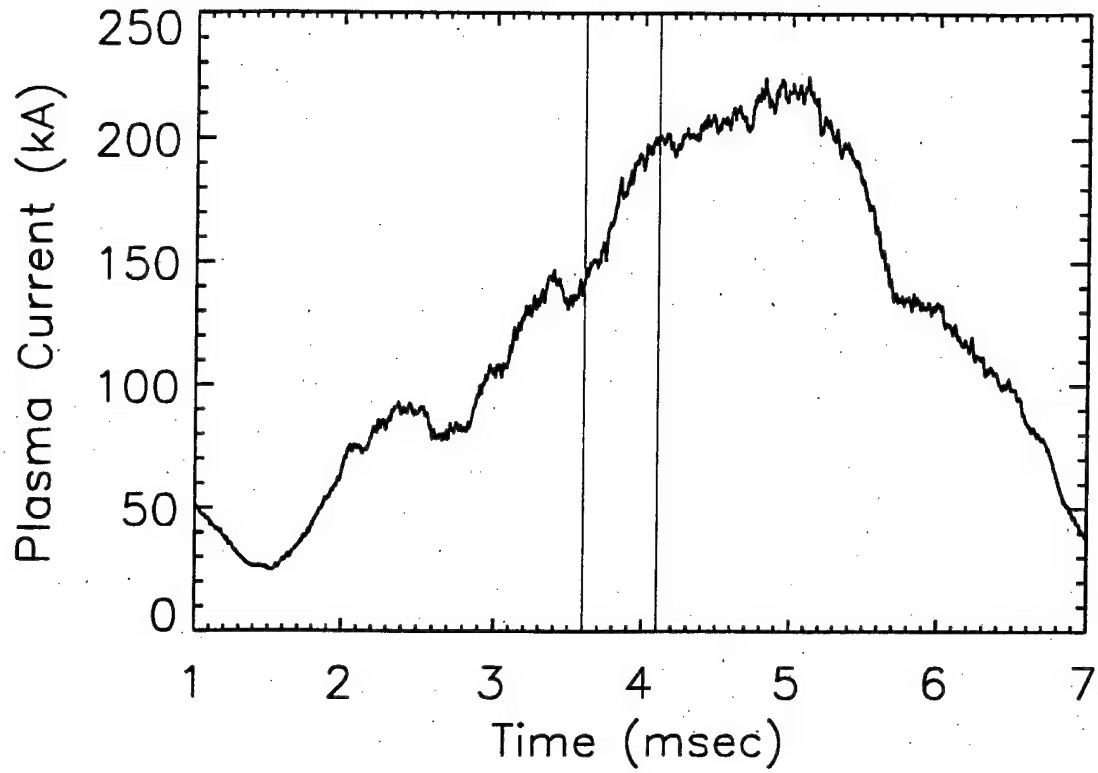

Figure 5.7 Plasma current during probe transit without a retroreflector sheet.

6. TRANSVERSE FIELD PROBE DESIGN

The development of the TIP diagnostic thus far, and its application to plasma field measurement in HIT, has focused on determination of the component of magnetic field along the probe's trajectory. [Strictly, the probe measures the field component along the propagation vector of the laser beam within the probe, which is not coincident with the *probe* propagation vector if the probe is tilted.] Although a plasma field component along any direction could be measured by firing the probe in that direction, it is more advantageous to be able to select the spatial profile (probe path) and measured field component independently. Furthermore, mounting the TIP gun system at an arbitrary orientation is problematic. For these reasons, it is desirable to have a probe which can measure the component of field *transverse* to the probe axis. All information about the internal field along a chosen chord through the plasma could be derived from three shots, one using a longitudinal probe, and two shots with (orthogonal) transverse probes.

An early goal of the program was to construct a probe that could simultaneously measure all three components of B-field, by illuminating the probe with a beam having three wavelength components. Wavelength-selective reflectors within the probe package would direct the three wavelengths along three orthogonal axes within a cubic Verdet sample, and the detection system would isolate and separately analyze the polarization at each wavelength. Experience in fabricating and launching the simple longitudinal probes has shown that maintaining the integrity of a 3-dimensional probe would be very difficult with the existing gun. The acceleration profile would likely have to be moderated to achieve this ultimate goal. While this endeavor is worth pursuing in the future, we have investigated a more readily reachable approach of measuring a single transverse field component.

The transverse-field probe design shown in Fig. 6.1 was strongly influenced by the need to minimize sheer forces during acceleration. Generation of polarization rotation by a transverse field component ("y" direction) is accomplished by propagating the beam obliquely in the Verdet sample, with reflections at the side walls. The key requirement of the design is that the net travel in the positive and negative y-directions be equal. For this condition, the longitudinal field component has no effect on polarization. Except for the marginal rays, this requires 2N reflections (N=1,2,3,...). The most practical case from a design standpoint is N=1 (2 reflections), for which the effective path length contributing to polarization rotation due to B_y is 4H, where H is the transverse dimension of the probe. Using the same Verdet samples as for the longitudinal probe (4 mm square cross-section

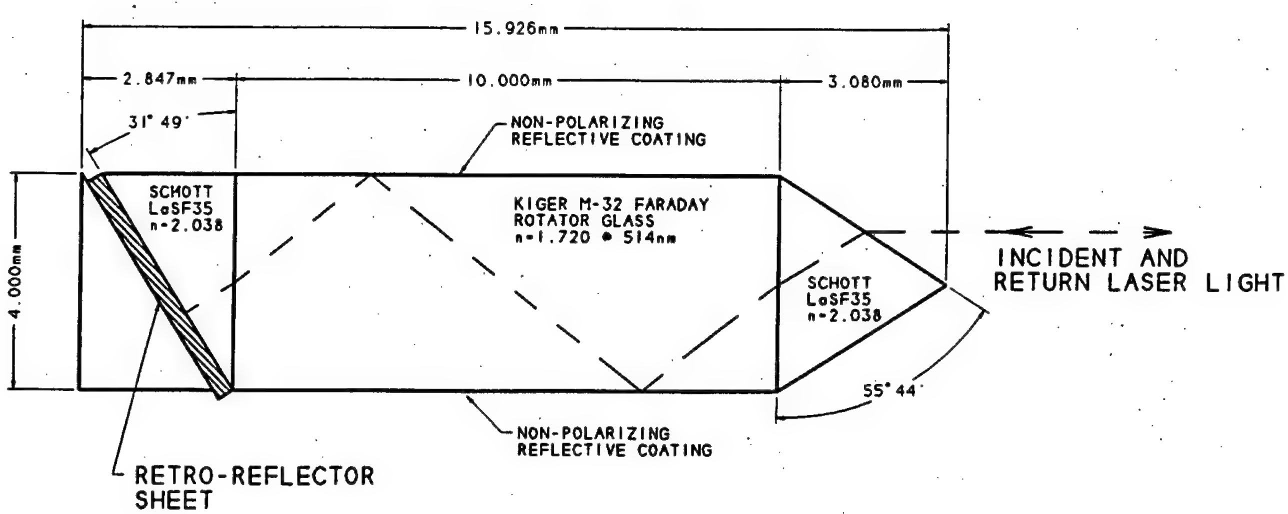

Figure 6.1 Schematic of TIP probe design for measurement of transverse fields.

by 10 mm long) the sensitivity to B_y is 75% of that of the longitudinal probe to B_x, and the propagation is inclined at θ=38.66° from the probe axis ("x" direction).

A prism of high refractive index is mounted on the front face of the rectangular Verdet sample, to refract the beam at the required angle θ. One of the oblique entrance faces of this prism is opaque, since the polarization rotation of light entering each of the oblique faces is in the opposite sense (no net effect). After passing through the Verdet sample the light is again refracted by a prism attached to the rear face of the sample, in such a way that the beam is incident normally onto a retroreflector sheet cemented to the prism's back face. This is done to minimize the effect of the retroreflector on polarization and ellipticity, which increases with angle of incidence. A third "dummy" prism is cemented to the backside of the retroreflector to create an thrust surface normal to acceleration. The only shear exists at the faces of the retroreflector. The laser beam returns along its "sawtooth" entrance path in the probe, and back to the ellipsometer.

A critical aspect of this probe design is that reflection at the probe sidewalls not contribute a spurious polarization effect. It was found that neither total internal reflection nor use of a simple metallic coating would meet this requirement, because of difference of phase and amplitude between reflected s and p components. An examination of various multilayer designs did show it possible to achieve the desired reflective characteristics. The simplest of these is a dielectric film deposited on the sidewall, overcoated with a metallic film. The dielectric film's index and thickness depend on θ, the Verdet index n_V, and the complex index of refraction of the metal overcoat.

Using an aluminum overcoat (complex index of refraction n_{Al} = [0.715,5.70] at 514 nm), and a dielectric film of index n_f=2.05 (based on materials available from the optical fabricator), the optimal coating thickness is 0.1176 λ or 60.4 nm over the M-32 verdet material (n_V=1.72). Fig. 6.2 shows the computed response of the probe (polarization angle and ellipticity angle of return light) vs transverse field, at longitudinal fields of 0, 0.5, and 1.0 Tesla. It is seen that the longitudinal field component has virtually undetectable effect on the response, as desired. Although the polarization of return light deviates from linearity with transverse field, this is easily accounted for in data analysis.

Several probes of this design were assembled and tested for integrity under gun acceleration. Although unpotted probes fitted in the same sabots used for the longitudinal probe did not survive, the use of a lighter weight probe (using crown glass in place of Verdet material), potted in an ULTEM jacket and fitted in a sabot with a larger bore, was successful, indicating the potential for this design to be useful for TIP. The weakest link structurally is the obliquely-mounted retroreflector sheet. This design will be examined in

the proposed program to minimize the problematic sheer forces by use of shorter probes and by use of a moderated acceleration profile for the gun.

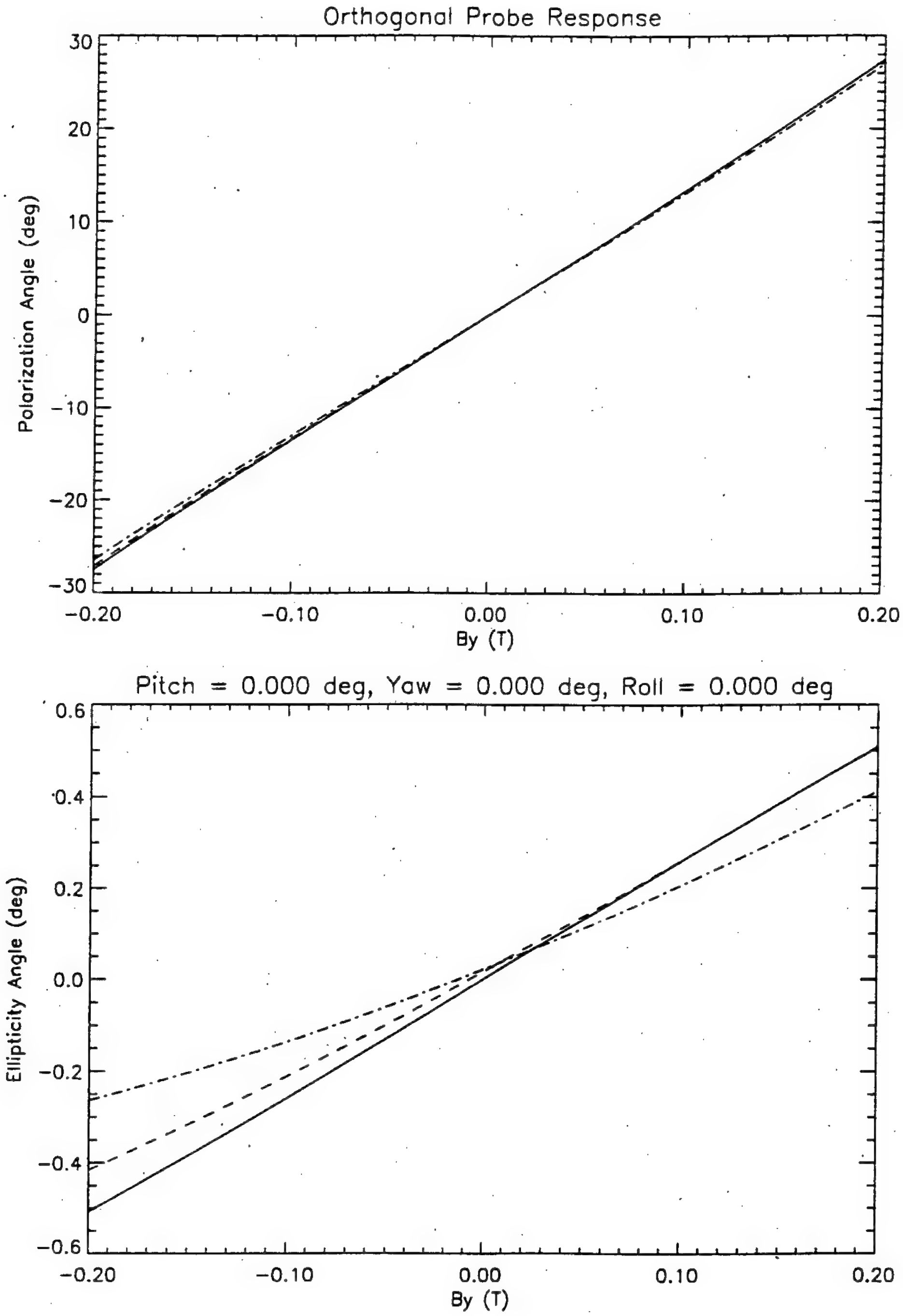

Figure 6.2 Computed optical response of orthogonal TIP probe to transverse fields (B_y) for various longitudinal field strengths (B_z).
Solid line: B_z=0, dashed line: 0.5 Tesla, dash-dot: 1.0 Tesla.

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Appendix A

The transient internal probe: A novel method for measuring internal magnetic field profiles

***Rev. Sci. Inst.* 66, p. 1197 (1995).**

The transient internal probe: A novel method for measuring internal magnetic field profiles[a)]

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(Presented on 10 May 1994)

The transient internal probe (TIP) diagnostic is designed to permit internal magnetic field measurements in hot, high density plasmas. A small probe is fired through the plasma at high velocities and magnetic field measurements are accomplished using Faraday rotation within the Verdet glass probe. Magnetic field resolution of ±40 G and spatial resolution of 5 mm have been achieved. System frequency response is 10 MHz. Ablative effects are avoided by minimizing both the probe size and the time the probe spends in the plasma. A two-stage light-gas gun is used to accelerate the probe (held by a sabot) to 2.2 km/s. The sabot is removed using gas dynamic forces and a gas interface system prevents the helium muzzle gas from entering the plasma chamber. Work is underway to integrate the TIP diagnostic with laboratory plasma experiments.

I. INTRODUCTION

One of the most difficult problems in magnetic fusion research is the measurement of the magnetic fields internal to the plasma in a nondisruptive fashion. The transient internal probe (TIP) diagnostic, currently under development at the University of Washington, allows these measurements by firing a small probe through the plasma at high velocities to minimize the disturbance of the plasma.[1]

A two-stage light-gas gun is used to accelerate the probe to velocities in excess of 2 km/s. The Verdet glass probe responds to the strength of the local magnetic field by changing the polarization angle of incident laser light passing through it. The polarization angle is measured by an optical detection system outside of the plasma.

The degree to which the probe is susceptible to ablative effects will determine the plasma density and temperature regime in which the TIP diagnostic can be used. To prevent ablation in very hot, dense plasmas, the probe can be coated with refractory material, such as diamond, or greater velocity can be imparted to the probe.

Work is currently being conducted to integrate the TIP diagnostic with laboratory experiments. Following a successful high-speed measurement (2.2 km/s) of a static magnetic field in a vacuum, the TIP diagnostic will be installed on the helicity injected torus (HIT)[2] at the University of Washington.

II. DIAGNOSTIC APPARATUS

The TIP diagnostic attached to a plasma experiment is shown in Fig. 1. A two-stage light-gas gun accelerates the probe (housed in a plastic sabot) past the gas expansion holes in the gun barrel. The sabot then separates axially from the probe. In the surge tank, the sabot is deflected off-axis and stopped while the probe is allowed to pass through into the plasma chamber. The laser light that passes through the probe is directed back toward the source by means of a retroreflector mounted on the probe's back face. In the double pass through the probe, the laser light's polarization is rotated in proportion to the magnitude of the local magnetic field component in the direction of the probe axis. The new polarization of the returned light is resolved by a detection system that is external to the plasma experiment. The probe then passes through a breakable mirror and is decelerated in the catch tank. Contamination of the plasma chamber is prevented by two fast valves that are used to stop the muzzle gases of the gun and debris from the probe's deceleration.

A. Probe acceleration

A two-stage light-gas gun for accelerating the probe into the plasma chamber has been designed, constructed, and thoroughly tested. The gun consistently accelerates 2.3-g probe/sabot projectiles (0.4 g for the 4 mm square probe and 1.9 g for the 50 caliber sabot) to velocities of 2.2 km/s. This speed is suitable for initial validation of the TIP diagnostic on the HIT plasma. Scaling these results to the maximum allowable breech pressure, it is expected that speeds of 4.5 km/s should be obtainable for use with hotter plasmas.[3]

The TIP two-stage light-gas gun is designed for maximum compatibility with plasma experiments. Compressed gas instead of explosives is used to drive the piston. A low-z propellant gas, such as hydrogen or helium, minimizes the possibility of contaminating the plasma vacuum system. Unlike most standard two-stage light-gas guns, the free piston in the TIP gun does not destroy itself every shot by colliding with the central breech. The rapidly increasing pressure of the propellant gas decelerates the piston before the projectile is released. This makes the TIP two-stage gun highly reliable and reproducible. Over 250 shots have been fired with negligible wear on the gun components.

[a)]The abstract for this paper appears in the Proceedings of the Tenth Topical Conference on High Temperature Plasma Diagnostics in Part II, Rev. Sci. Instrum. **66**, 661 (1995).

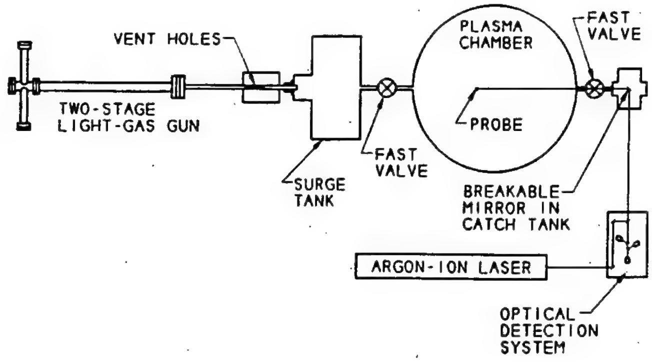

FIG. 1. TIP diagnostic layout.

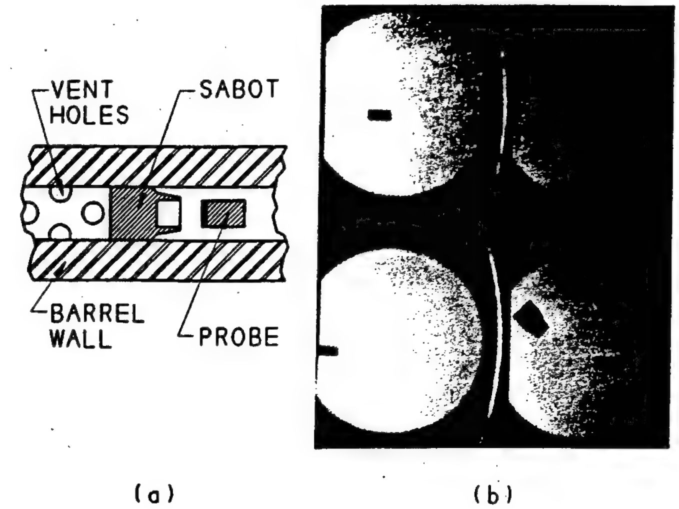

FIG. 2. (a) The sabot axially separates from the probe while in the gun barrel. (b) A probe traveling through a vacuum at 2.2 km/s followed by a separated and deflected sabot. The direction of travel is from left to right. Photos were taken 10 μs apart.

B. Sabot removal

As in many ballistic research applications, the TIP diagnostic requires a sabot to hold the payload (magneto-optic probe) during acceleration in the gun. Lexan® was chosen as a sabot material because of its toughness, light weight, and easy machinability. Because the sabot material will contaminate the plasmas to which TIP is intended to be applied, the sabot must be separated from the probe and stopped prior to the probe's entry into the plasma.

The sabot removal scheme that has been successfully implemented for the TIP diagnostic uses gas dynamic forces to axially separate the sabot from the probe while both are still in the gun barrel. A 0.0005 in. thick mylar window at the gun muzzle separates the barrel from the vacuum system which allows the barrel to be filled with nitrogen at 1 atm. When the gas gun is fired, the nitrogen present in front of the probe/sabot projectile is compressed by a normal shock wave that develops during the probe/sabot acceleration. As the probe/sabot projectile passes the radial vent holes in the barrel, the propellant pressure is greatly reduced. The sabot, which forms a seal with the barrel wall, experiences a net pressure force in the rearward direction while the subcaliber probe encounters negligible pressure forces. This causes the sabot to axially separate from the probe as shown in Fig. 2(a). Once free from the confines of the sabot, the probe experiences very little relative "wind" because the shocked nitrogen in which the probe travels is moving at a similar velocity to the probe. This combined with reduced muzzle blast due to the vent holes provides a sabot removal technique that minimizes the forces that could possibly perturb the flight of the probe. Downstream of the gun muzzle, a small angle deflector plate in the surge tank deflects the sabot off course but clears the subcaliber probe, allowing it to travel through a small tube into the plasma chamber.

Gas dynamic sabot removal has been repeatedly tested in our laboratory and is very successful. Figure 2(b) is a photograph taken 1 m down range of the gun barrel in the surge tank. It shows a stable probe traveling at 2.2 km/s followed by a separated and deflected sabot. The 3-cm separation distance observed in the photograph is typical and the deflection of the sabot is very reproducible.

C. Magneto-optic probe

Faraday rotator magnetic field probes (10×4×4 mm) have been constructed using terbium-doped borosilicate glass (FR-5)[4] as the Verdet material. The FR-5 glass material has a Verdet coefficient of 0.0066 deg/G cm at the 514-nm wavelength of the argon–ion laser. Retroreflection is accomplished using a corner-cube sheet attached to the rear face of the probe. The use of this material is advantageous because it allows a compact and lightweight design. Measurements indicated that little absorption or scattering occurred for the sheet, but that the return light was spread over a full angle of about 5°, due to the nonideal nature of the microprism retroreflectors on the sheet. Nevertheless, at the laser powers used, sufficient return light is collected to give a good signal-to-noise ratio.

D. Optical detection system

The purpose of the optical detection system is to measure the rotation of the polarization angle due to the Faraday effect. The system uses three detectors, each responding to a different polarization, to provide maximum sensitivity and to allow for variations in intensity of the returned light.[5] The relationship between intensity and power is

$$P = E_0^2 \cos^2 \psi. \tag{1}$$

Ideally, ψ could be determined directly by comparing the reduction in signal to a signal from a known polarization angle. However, other factors such as wave attenuation and background light sources, affect the amplitude of the incoming signal. Taking these factors into account with a scaling factor, C, and an offset, Σ, the power equation then becomes

$$P = C \cos^2 \psi + \Sigma. \tag{2}$$

Having three unknowns requires the use of three detectors with polarizing filters set at different angles. If the filters are set 60° apart, the angle ψ can be solved for by using a least-squares method. The result is

$$\tan(2\psi) = \left\{ \frac{\sqrt{3}(P_3 - P_2)}{2P_1 - P_2 - P_3} \right\}. \tag{3}$$

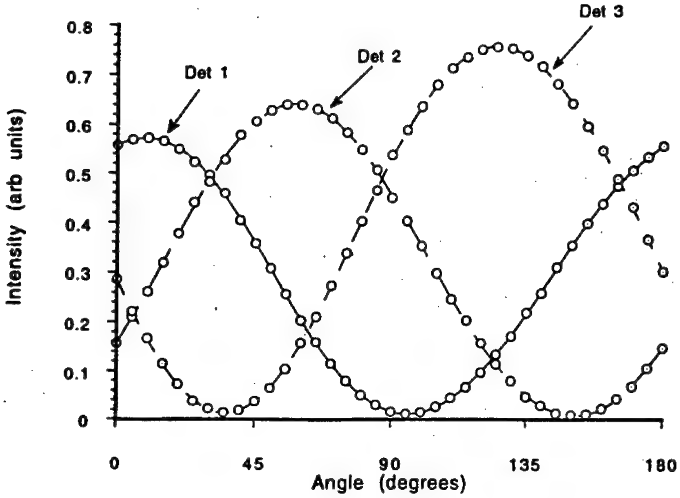

FIG. 3. Response of the three detectors to polarized calibration light. The open circles are normalized detector signals and the dotted lines are the ninth-order polynomial fits.

This result, however, is valid only if $\alpha_1=0°$, $\alpha_2=60°$, $\alpha_3=120°$, and the returning light is perfectly linear.

In general, the detector polarizing filters will not be set exactly 60° apart and the light will not be perfectly linear. This can be accounted for by calibrating the system for arbitrary angles. A source of known polarized light is passed through the system and the detector responses are recorded. The resulting calibration curves can be represented by three ninth-order polynomials:

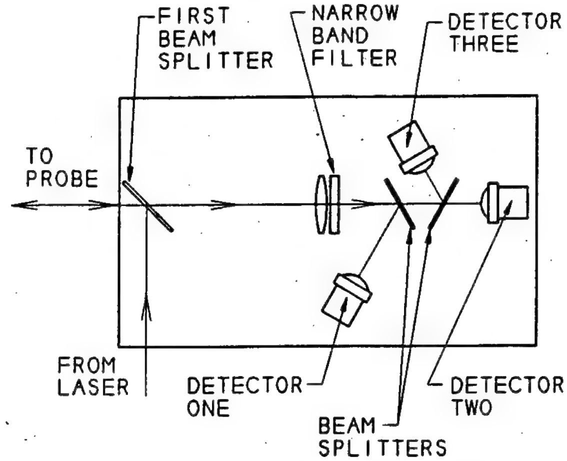

FIG. 4. Optical detection system layout.

$$I_i=\sum_{n=0}^{9} a_{i,n}\psi^n, \tag{4}$$

where $i=1$, 2, or 3 for the three detectors. These calibration curves are shown in Fig. 3. Measurement of the polarization angle for arbitrary return light is achieved using an iterative method involving the least-squares approximation

$$R=\sum_{i=1}^{3} (I_i-P_i)^2. \tag{5}$$

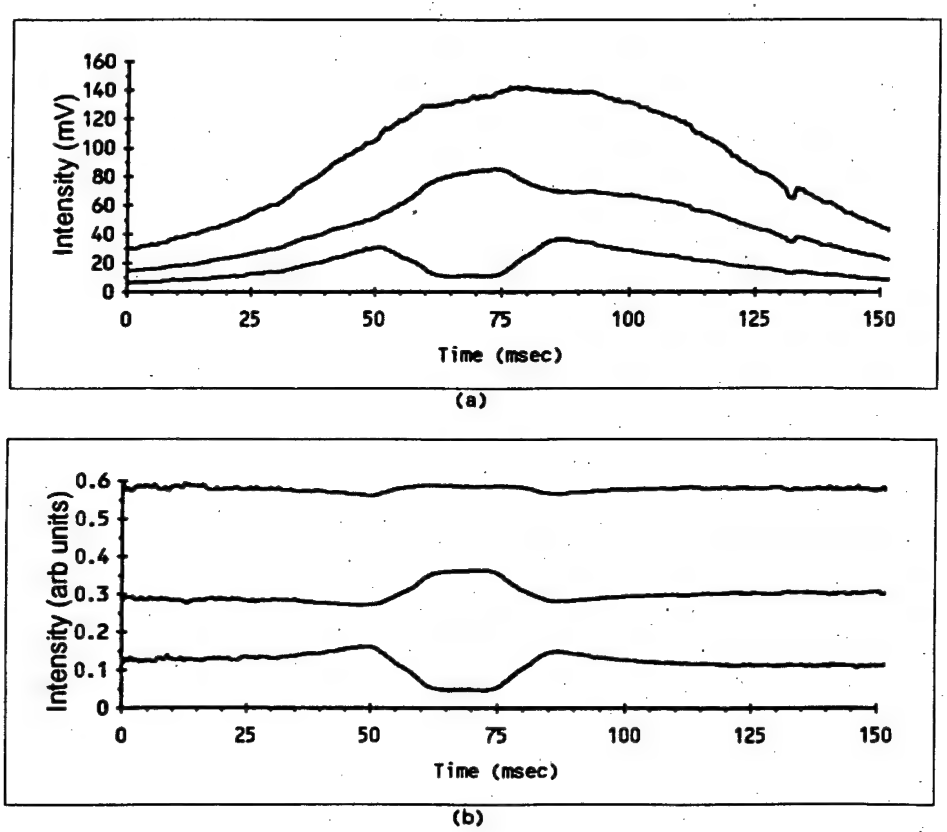

FIG. 5. (a) Raw signals produced by the probe moving through a magnetic field. The overall rise and fall of the signals masks the Faraday effect. (b) Signals after normalization. The overall variation in the signals has been removed making the Faraday effect much more visible.

Setting $dR/d\psi=0$ and using a root finding algorithm, the polarization angle is determined. The starting point for the iteration process is given by Eq. (3). Measurements in the absence of a magnetic field provide a base line value of ψ_0 such that

$$B=2LV(\psi-\psi_0), \tag{6}$$

where L is the length of the Verdet material and V is the Verdet coefficient.

A schematic of the optical detection system is given in Fig. 4. The argon ion laser beam is expanded and directed by a mirror to the first beam splitter. The first beam splitter then directs half of the beam toward the probe, which retroreflects light back to the splitter. The return beam then passes through a focusing lens and a narrow-band (10 nm) filter passing the 514-nm wavelength. The beam is then split three ways and directed to the three detectors. In front of each detector is a polarizing filter, and the three polarizers are offset by 60° as described above.The spacing of optical components was chosen such that the incident angles on optical components remain small to minimize measurement errors.

E. Magnetic field measurement

To demonstrate the ability to track a moving probe while accurately measuring the change in polarization angle, a TIP probe was dropped through a permanent magnet and the optical detection system was used to measure the local magnetic field. By performing many drops and comparing the spread in the optical detection system response, we were able to determine the accuracy of the system. The probe used for this experiment was identical to the probe that will be used to make measurements in a plasma.

Figure 5(a) displays the raw signal data and Fig. 5(b) displays the normalized signal data. As expected, the signal amplitude varied significantly during the probe drop. This variation is removed by normalizing the signals, such that only the amplitude change due to the Faraday effect remains. Normalization is achieved by simply dividing each signal by the sum of all three signals. Once normalized, the data is ready for analysis using the procedure mentioned above.

Figure 6 shows data that is analyzed as described above to yield the magnetic field vs position. The TIP measurement is seen to agree well with magnetic field measurements using a Hall probe, especially near the coil ends where the same low magnitude field asymmetries are seen by both measurements. The field strength error bars for the TIP measurement correspond to the maximum range seen from several separate measurements and give an average error of ±40 G. This corresponds to a polarization angle resolution of 0.25°.

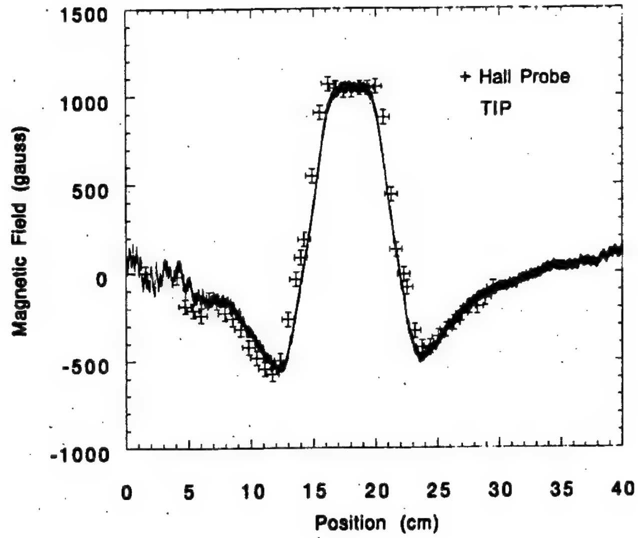

FIG. 6. Magnetic field measurement by a moving TIP probe shows excellent agreement with Hall probe measurements. TIP measurement error is ±40 G with a spatial resolution of 5 mm.

III. CONCLUSIONS

The two-stage light-gas gun and the sabot removal hardware have been developed and thoroughly tested. The probe consistently has excellent flight properties 3 m from the gun muzzle while traveling at 2.2 km/s. Also, the sabot is consistently removed from the probe, deflected, and stopped so that only the probe is observed to transit the plasma chamber. Measurements indicate that a 15-ms delay exists from when the probe enters the plasma chamber to when a 0.5-Torr ℓ pressure rise is detected in chamber, which is substantially more than the time needed to shut a fast valve.

The optical detection system has been successfully tested and the response of the Verdet material to known magnetic fields has been characterized. The resolution of the measurement is seen to be ±40 G with a spatial resolution of less than 1 cm.

Following the successful free flight measurement of a static magnetic field in a vacuum, testing of the TIP diagnostic for actual plasma measurements will be performed by installing the apparatus on HIT in late 1994.

ACKNOWLEDGMENT

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Appendix B

Magnetic field measurements using the transient internal probe (TIP)

***Rev. Sci. Inst.* 67, p. 469 (1996).**

Magnetic field measurements using the transient internal probe (TIP)

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The transient internal probe (TIP) is a novel diagnostic technique for measuring magnetic fields in hot plasmas. The concept involves shooting a diamond clad magneto-optic probe through the plasma at high velocity allowing measurement of the local magnetic field before ablation occurs. Magnetic field measurements are obtained by illuminating the probe with an argon laser and measuring the amount of Faraday rotation in the reflected light. The diagnostic was tested by measuring a permanent magnetic field inside a vacuum chamber with a probe traveling at 2 km/s using an unclad probe. The purpose of this experiment was to demonstrate the capability of the TIP diagnostic and to verify compatibility with plasma vacuum requirements. Magnetic field resolutions of 20 G and 1 cm spatial resolution were achieved. The response time of the detection system is 10 MHz. Introduction of a helium muzzle gas into the plasma chamber was limited to less than 0.4 Torr ℓ.
 [S0034-6748(96)00502-0]

I. INTRODUCTION

Understanding the behavior of hot plasmas is central to developing magnetically confined fusion into a productive energy source. A significant impediment to this understanding is the difficulty of measuring the internal magnetic field profile of hot plasmas in a nonperturbing manner. Several methods have been employed with varying degrees of success. The transient internal probe (TIP) diagnostic is designed to provide a highly accurate direct measurement of the internal magnetic field profile.

Currently, for large tokamaks, most internal magnetic field profiles are obtained by utilizing the motional Stark effect.[1–3] A neutral beam is injected into the plasma and in the presence of a large magnetic field, sufficient Stark splitting of the H_α line occurs to resolve the $\Delta m=0,1$ transitions. The $\Delta m=1$ or σ transitions are polarized parallel to the local magnetic field. By measuring the polarization of the emitted light, determination of the local pitch angle is possible. Assuming the torroidal field is known, the poloidal field can be calculated. This diagnostic technique has been successful, but its effectiveness is limited. The neutral beam is inherently perturbing to the plasma and the time response for the system is limited by the necessity of collecting sufficient light for good accuracy, typically on the order of 1 ms. Finally it is inappropriate for configurations without a strong torroidal field.

Another method for measuring internal fields is heavy ion beam probing (HIBP). HIBP involves shooting heavy ions into the plasma and following their trajectory. Assuming the torroidal field is known, variations in the torroidal position of the ejected particle provides information about the poloidal field. This method has the advantage of good time response, allowing measurement of internal magnetic fluctuations.[4] But it too requires a perturbing beam and requires significant knowledge of the fields prior to use in order to calculate the particle trajectory and isolate the desired effect.

Multichord Faraday rotation polarimetry is another technique which has been effectively used to measure internal magnetic field profiles in plasmas.[5–7] This technique utilizes the Faraday rotation of a long wavelength laser to determine the chord averaged magnetic field. The magnitude of the Faraday rotation is given by

$$\alpha=c_f\int n_eB_z dz, \tag{1}$$

where α is amount of rotation and c_f is a constant. If the electron density profile is known and several chords are measured the magnetic profile can be obtained by using an Abel inversion. This method has the advantage of being completely nonperturbing to the plasma. The time response is limited by the type of polarimetry, but typically is 1 ms or less. The disadvantage of this technique is that the measurement is a chord average and it requires knowledge of the electron density profile.

Other methods such as measuring the tilt angle of injected impurity pellets,[8] or observation of Zeeman splitting in light emission from lithium pellets[9,10] have been used. Both of these methods are perturbing and somewhat limited in accuracy relative to the methods discussed above. For configurations without internal diagnostics the profile is inferred from solutions to the Grad–Shafronov equation fit to the data from external probes measuring global parameters. Unfortunately a large number of internal profile solutions can match the surface measurements.

The TIP concept[11,12] involves shooting a small probe (4 mm×4 mm×1 cm) through the plasma at high velocity (2–5 km/s) with a two-stage light gas gun. The probe is made of a high verdet material consisting of terbium-doped borosilicate glass with a retroreflecting sheet comprised of an array of microcorner cubes attached to the rear surface. The probe and corner cube can be encased in a protective diamond cladding. Currently, unclad probes are being used. Measurements are conducted by illuminating the probe with a linearly polarized laser and continuously measuring the amount of Faraday rotation in the light reflected from the probe back to the optical detection system.

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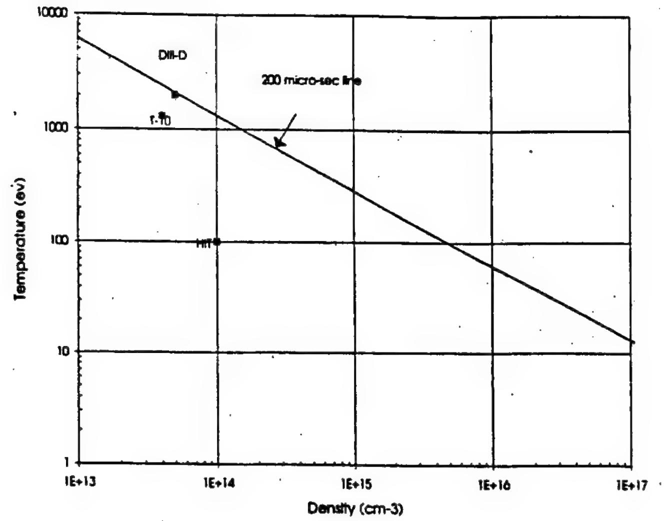

FIG. 1. Plot of constant "belief time," as a function of density and temperature.

II. PROBE SURVIVABILITY

Central to the TIP concept is the survivability of the probe in a hot plasma environment. In order to discuss probe endurance, the "belief time," t_b, is defined as the time required for the surface of the probe to reach the boiling point thus allowing ablation to occur. Although the probe likely will function beyond this time, restricting the probe to this regime limits the introduction of impurities into the plasma and eliminates concerns about trajectory deviation due to asymmetrical jetting of the ablated surface.

Estimation of the belief time is done using a method described in Ref. 13 by Lovberg. Heat loading to the probe is assumed to be the particle collision rate times the average energy per particle reaching the probe. The collision rate for this calculation is simply

$$\upsilon=\frac{n v}{4}, \tag{2}$$

where υ is the average velocity and n is the density. From Eq. (2), the electrons will have a higher collision rate, since their average velocity exceeds the ion velocity by the square root of the ratio of ion mass to electron mass. Since the probe is an insulator, a negative sheath develops reducing the flux rate of particles to the probe to the ion rate. Taking this into account and assuming $T_i=T_e$ the energy deposition rate to the probe is

$$P=\frac{n_i}{\sqrt{2\pi m_i}}(kT)^{3/2}\left[\frac{1}{2}\ln\left(\frac{m_i}{m_e}\right)+4\right]. \tag{3}$$

The belief time is found using the results of Ashby[14] for surface heating of insulators

$$t_b=\frac{T^2(\pi\rho\kappa C)}{P^2} \tag{4}$$

where P is the heat loading calculated above, T is the boiling temperature, κ is the thermal conductivity, C is the heat capacity, and ρ is the density of the probe. Several belief times have been calculated assuming a diamond-coated probe and are shown in Fig. 1. Also plotted are some familiar fusion devices. These calculations are believed to be conservative since they ignore cross field reduction of flux and assume constant temperature and density profiles. Increasing the TIP velocity to 5 km/s and encasing the probe in diamond would allow complete radial probing of DIII–D. The degree to which the probe is susceptible to ablative effects will determine the plasma density and temperature regime in which the TIP diagnostic can be used.

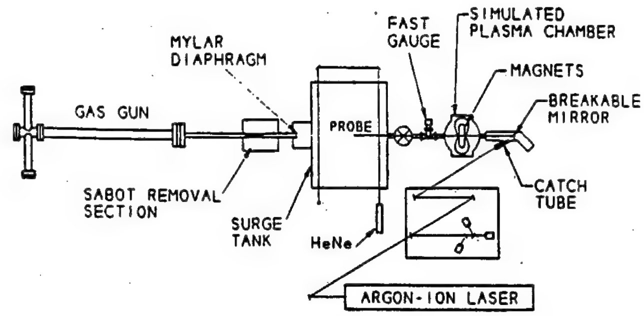

FIG. 2. Experimental setup for testing the transient internal probe (TIP).

III. EXPERIMENTAL ARRANGEMENT

In preparation for measurements in a plasma the TIP concept has been demonstrated by measuring a permanent magnetic field inside a vacuum vessel. The layout for the demonstration experiment shots is shown in Fig. 2. The vacuum boundary consists of an expansion tank, a simulated plasma chamber which holds the permanent magnet, and a catch tube. A 0.0005-in.-thick Mylar diaphragm serves as the vacuum barrier between the bore of the gun and the vacuum tanks. The base pressure for the vacuum tanks is typically 3×10^{-6} Torr. Prior to the shot the gun is aligned using a HeNe laser which is aligned with the desired bullet path. The argon laser is then aligned such that it reflects off the breakable mirror in the catch tube and down the bore of the gun.

A digitally controlled stepper motor initiates the firing sequence in which the probe, held in a protective Lexan sabot, is accelerated with a two-stage light gas gun. The probe travels through the sabot removal and gas expansion system, past the simulated plasma chamber, and into the catch tube. Total time from trigger initiation to the time the probe enters the plasma chamber was 71.9 ms, with an average variation of 0.6 ms. Axial separation of the sabot from the probe occurs in the barrel. Inside the expansion tank a stainless steel plate deflects the larger sabot off the probe trajectory and into a steel container. Two HeNe laser beams spaced nearly 1 m apart are aligned perpendicular to flight of the probe and onto a photodiode. Interruptions in this signal are noted and used to calculate probe speed and position. Once the probe exits the expansion tank and enters the plasma chamber, a fast valve (<5 ms) located at the entrance to the simulated plasma chamber closes to minimize admission of helium driver gas. Closing of this valve is initiated by the deflected sabot which breaks a wire that holds the fast valve open.

Throughout the flight, the probe is illuminated with 514

nm wavelength light from an 8 W argon ion laser. The beam is expanded to approximately 1 cm in diameter to ensure the bullet remains illuminated. Light reflected from the backsurface of the probe is collected by the optical detection system. This system consists of three detectors, each containing a photodiode and a linear polarizer oriented 60° from each of the other detectors. The system is calibrated by using a half-wave plate to vary the input polarization of a reference beam into the system and recording the output of the detectors. The data are normalized by dividing the individual signal strength by the total strength and then are used to generate a calibration curve for each detector. The polarization of an input beam can be determined by least-squares fitting the normalized signals to the calibration curves.

Once the polarization is known the magnetic field component parallel to the path of the probe is given by

$$B_{11}=\frac{\psi-\psi_0}{2LV}, \tag{5}$$

where ψ is the measured polarization and ψ_0 is the baseline polarization in the absence of a magnetic field, L is the length of the probe, and V is the Verdet constant. For this test, 1-cm-long by 4 mm×4 mm probes were used. The Verdet constant of each probe was measured using a 2 T magnetic resonance imaging magnet. For 514 nm light, the Verdet constant was 0.00716°/cm G. Uncertainty was less than 0.1%. Presently TIP is a single-shot system. Following each shot the breakable mirror is replaced and the surge tank and catch tank are pumped down to base pressure. Turnaround time between shots including pumpdown and alignment is 4 h. Descriptions of the operation of the gas gun, sabot removal system, and optical detection system are provided in Ref. 12.

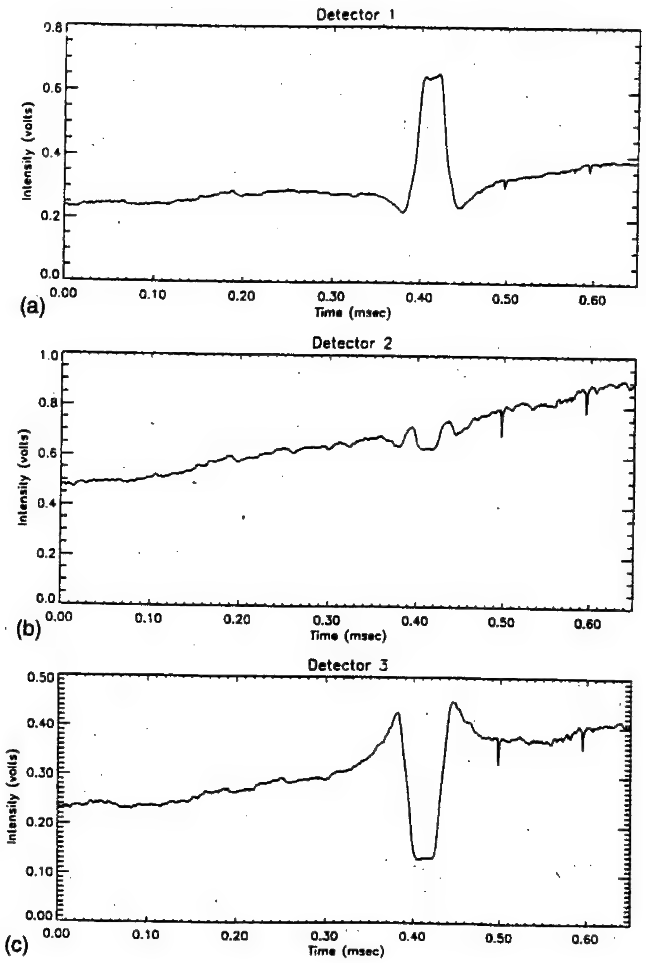

FIG. 3. (a)–(c) Detector signals received from probe in flight traveling at 2 km/s.

IV. MEASUREMENT RESULTS

The capability of the TIP diagnostic was demonstrated by measuring the field of a permanent magnet inside a vacuum chamber using a high speed unclad probe. Figures 3(a)–3(c) show the signals received on the three detectors during a shot. The data were taken at a rate of 1 MHz using a CAMAC 6810 digitizer. Initial polarization of the laser was nearly parallel to the transmission axis of detector 2. As the probe passes through the dipole magnetic field, rotation of the polarization is clearly observed. The overall increase in intensity is due to the probe getting closer to the collecting optics of the detection system. Figure 4 shows the detector signals normalized by their sum. The data are fit to the optical detection system calibration curves in order to determine the polarization of the reflected light. The local magnetic field is then deduced using Eq. (5).

Figure 5 shows the magnetic field profile measured using the TIP diagnostic. Plotted along with the TIP data are measurements taken with a Hall probe. The Hall data taken on this magnetic configuration are not appropriate for exact determination of the TIP resolution. The large gradients in the measured field and the uncertainty in the exact chord traveled by the probe through the magnets made the Hall data uncertain over 40 G. An independent calibration check of the polarimeter showed it to have an uncertainty of 0.3°. This results in a magnetic resolution of 20 g for a 1 cm probe. A spatial resolution of 1 cm is observed while collecting data at 1 MHz. The bandwidth of the detection system was determined to be 10 MHz by an independent measurement.

The amount of muzzle gas entering the simulated plasma chamber was determined by recording the pressure rise in the chamber. A baratron® gauge was used to make the measure-

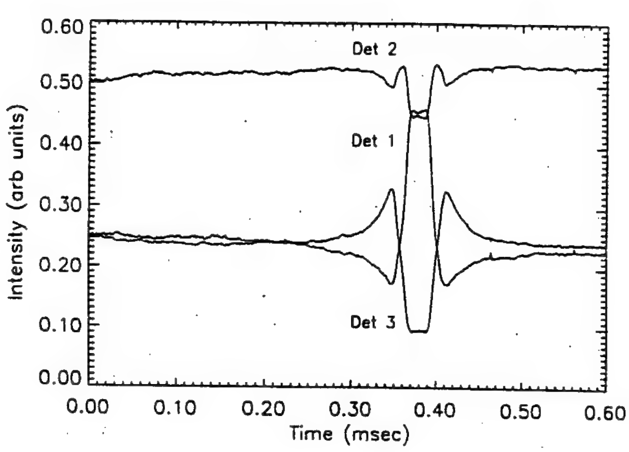

FIG. 4. Detector signals after normalization.

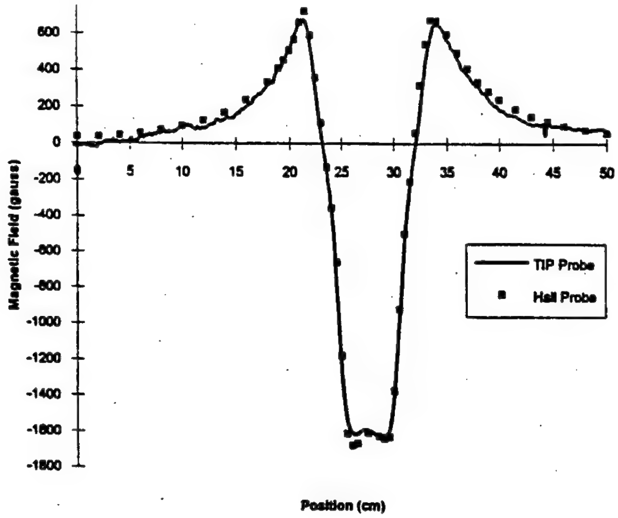

FIG. 5. Plot of magnetic field vs position using TIP. Overlaid are measurements made using a Hall probe.

ments. Typically the rise was 7 mTorr. The volume of the tank and associated connections was about 50 ℓ indicating an admission of less than 0.4 Torr ℓ of helium into the plasma chamber.

V. CONCLUSION

The TIP diagnostic is ready to perform internal magnetic field measurements on laboratory plasma experiments. All components of the diagnostic have been constructed and tested for reliability and compatibility with high vacuum systems. Work is now underway to perform the first TIP plasma measurements using uncoated probes on the Helicity Injected Torus.[15] Future work includes development of probes capable of measuring all three components of the magnetic field simultaneously.[16]

ACKNOWLEDGMENT

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Appendix C

Internal magnetic field measurements on the helicity injected tokamak using the transient internal probe

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Internal toroidal field measurements on the helicity injected tokamak using the transient internal probe

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(Presented on 13 May 1996)

Measurements of the local toroidal magnetic field have been achieved on the helicity injected tokamak (HIT) using the transient internal probe (TIP). HIT is a low aspect ($a=1.5$, $R=0.35$ m) ratio tokamak designed to study steady state current drive. The TIP diagnostic involves accelerating a small diamond clad magneto-optic probe through the plasma at high velocities (~2 km/s) using a light gas gun. The local field is obtained by illuminating the probe with a laser and measuring the amount of Faraday rotation in the reflected beam. Measurements were conducted using unclad magneto-optic probes directed along a chord tangent to the toroidal field. Plasma conditions were typically $n_e \sim 7\times10^{19}$ m^{-3} and $T_e \sim 40-80$ eV. Measurement uncertainty is less than 2%. No changes in plasma parameters were observed during the first 200 ms (~40 cm) of probe travel in the plasma. A temporary dip in plasma current, probably due to ablation of the retroreflecting material on the probe, is observed as the probe exits the plasma. Density is unaffected by the presence of the probe in the plasma. No long term deleterious effects to tokamak performance were observed as the TIP diagnostic was found to be quite compatible with the tokamak. [S0034-6748(97)53501-5]

I. INTRODUCTION

A number of tokamak experiments have reported dramatic results of improved energy confinement and stability through internal current profile control.[1,2] Discovery of these results was made possible by measurement of the internal q profile using the motional Stark effect (MSE) diagnostic. Unfortunately, the MSE diagnostic requires neutral beam injection and large magnetic fields, neither of which may be available for smaller scale tokamak experiments or alternative plasma devices. Surface heating which leads to ablation severely limits internal magnetic measurements using traditional probes. The transient internal probe (TIP) is designed to directly measure the internal magnetic field of hot plasmas (up to 2 keV using diamond clad probes). Briefly, the TIP concept involves shooting a small probe through the plasma at high velocity with a two stage gas gun. This allows probing of the plasma profile during any time of the discharge, while minimizing the exposure of the probe to the plasma to 500 μs or less. Measurement of the local magnetic field is achieved by illuminating the probe with a linearly polarized argon ion laser at 514 nm and determining the amount of Faraday rotation in the reflected light coming back from the probe. At this wavelength Faraday rotation in the probe is roughly 10^4 greater than in a 1 m path length through the plasma. Thus, Faraday rotation by the plasma is negligible. References 3 and 4 provide detailed descriptions of the diagnostic.

The concept has been successfully tested using unclad probes in the helicity injected tokamak (HIT) located at the University of Washington.[5] Though this particular experiment involved accelerating the probe through the plasma, the TIP concept is also ideally suited for measuring internal profiles of accelerated plasmas as they travel past a stationary probe.

II. DIAGNOSTIC ARRANGEMENT

The arrangement for the internal magnetic field measurements on HIT are shown in Fig. 1. The system consists of the gas gun, expansion tank, catch tank, and optical detection system. Operation of the diagnostic with the tokamak occurs as follows. During charging of the tokamak capacitor banks, the gas gun is manually pressurized from the control room and the firing sequence is initiated 53.6 ms prior to plasma formation. This time is required for the gas gun to reach peak pressure and launch the probe. Once launched, ~2 ms are required for the probe to be accelerated and travel to the plasma chamber. Throughout its flight, the probe is illuminated with the argon laser and reflects light back to the detection system until it hits the breakable mirror in the catch tank. Presently the gas gun is being operated to accelerate the probe to 1920 m/s±1%. "Jitter" in the firing sequence is less than 1 ms.

The expansion tank is designed to minimize the amount of helium driver gas that enters the plasma chamber. The tank is pumped down to a base pressure of $\sim 3\times10^{-6}$ Torr providing a large surge volume to catch the gas from the barrel. A fast valve with a 4 ms closing time is actuated as the probe exits the expansion tank, further limiting the amount of helium entering the tokamak. Total gas entering the system is about 0.4 Torr-l of helium. Note that hydrogen is the preferred driving gas, but helium was used to reduce gas handling complications. Standard electropneumatic high vacuum valves are closed immediately following the shot, providing long term high quality vacuum integrity.

The catch tank is also pumped down to a base pressure of less than 3×10^{-6} Torr. This tank houses a mirror which directs the illuminating laser light to the probe and reflected

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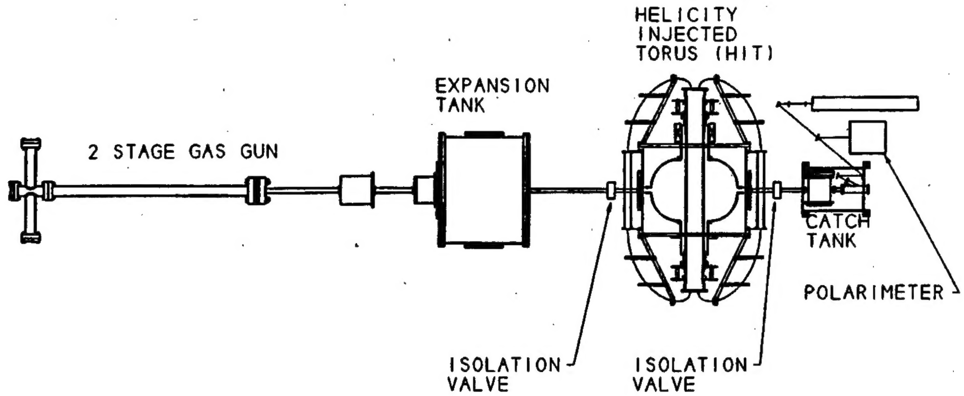

FIG. 1. Top view of helicity injected tokamak with TIP diagnostic.

light back to the detection system. The tank also contains the debris generated when the probe impacts the mirror. Adjacent to the catch tank is the optical detection system which consists of an 8 W argon ion illuminating laser and a polarimeter used to analyze the polarization state of the reflected light.

Cycle time for the gun and vacuum components is ~1 h with an additional 4 h required for pumpdown of the systems. Typically two shots per day are conducted with normal tokamak operation conducted during pumpdown in between shots.

III. RESULTS OF PLASMA MEASUREMENTS

Several internal magnetic field measurements have been conducted on the helicity injected tokamak. A close up view of the probe trajectory through the tokamak with the location of the toroidal field coils and return bundles is shown in Fig. 2. Signal data from each of the three detectors for one shot are presented in Fig. 3. These signals were digitized using a 12 bit digitizer at 1 MHz. Each detector has a linear polarizer oriented 60° relative to the adjacent detector. The data shown in Fig. 3 are the photodiode output of each detector. These data are normalized by dividing each signal by the total received signal in order to take into account for variations in laser illumination during flight. The normalized data are then fit to calibration curves in order to determine the polarization angle of the returned light. Once the polarization is known, the local magnetic field is easily determined by multiplying with the appropriate verdet coefficient. Figure 4 shows the analyzed data plotted with the calculated vacuum magnetic field. The vertical lines located at −46 cm and 46 cm indicate the boundary of the outer wall of the plasma chamber. The field variations at 130 and 160 cm are due to permanent magnets placed in the system to measure pitch and yaw of the probe. Illumination of the probe at the end of its flight was poor resulting in a poor signal to noise ratio in that

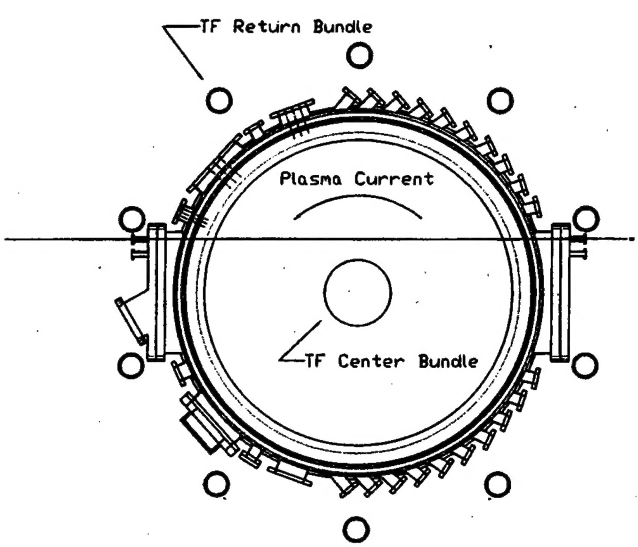

FIG. 2. Side view of TIP trajectory through the tokamak.

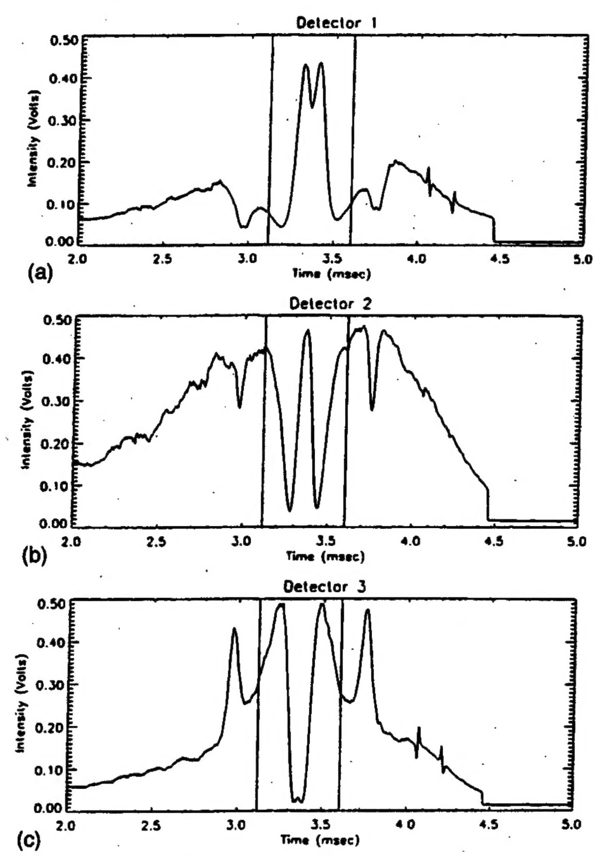

FIG. 3. (a)–(c) Detector signals received from probe traveling through tokamak at 2 km/s. Vertical lines indicate plasma chamber boundaries.

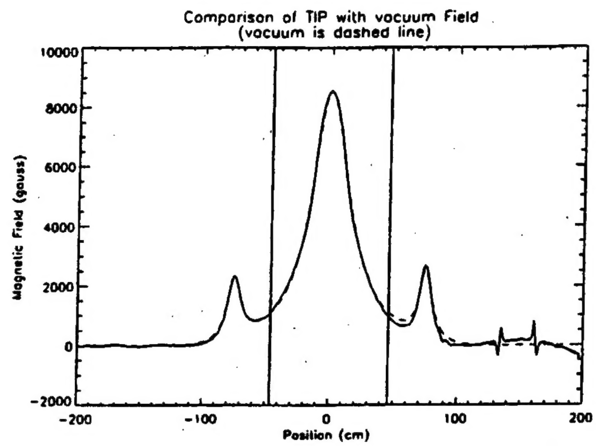

FIG. 4. Magnetic field measured by TIP along chord tangent to the toroidal field at $R=18$ cm plotted with the calculated vacuum magnetic field.

region. Figure 5 plots the measured magnetic field with the calculated vacuum magnetic field subtracted. Some of the modulation in the residual field is due to the plasma but comparisons with the region outside of the plasma chamber and with shots conducted with no plasma, indicate some systematic uncertainty in the measurement is present. This problem is particularly evident in the latter half of the measurement resulting in an uncertainty of 200 G, or ~2.5% of the measured field.

Two factors are likely contributing to the majority of this uncertainty. The first is the optical detection system model used to determine the polarization of the light. Presently the system assumes completely linear light. This assumption, though acceptable to first order, is not correct. Reflections off of the corner cube retroreflector, steering mirrors, and beamsplitters, result in elliptic polarization. Consequently an ellipsometer is being developed to more accurately measure the polarization state of the reflected light. Testing and installation of the ellipsometer is now being conducted. The second major contributor to the uncertainty in the measurement is uncertainty in the probe's spatial orientation as it travels through the plasma. Because of the large gradients in the magnetic field, small amounts of pitch and yaw can have a significant effect on the measurement. Efforts are also underway to reduce this uncertainty. The overall goal is to achieve an absolute accuracy of less than 15 G.

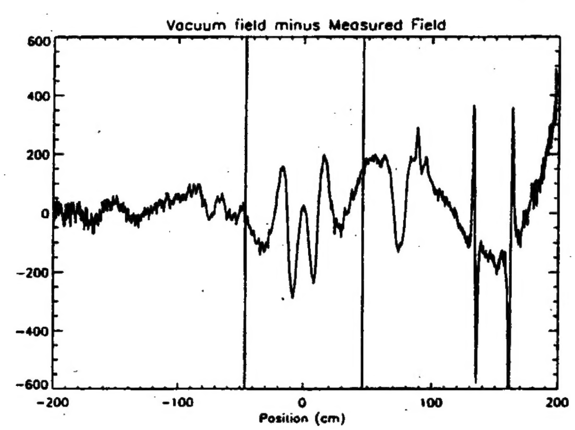

FIG. 5. Residual magnetic field after calculated vacuum field has been subtracted from the measured field.

Perturbation to the plasma is minimal during the first 200 μs of probe presence in the plasma. After this time, a drop in plasma current is usually observed, apparently due to ablation of the retroreflector material on the rear of the probe. Shots have been taken in which the retroreflector material came off during acceleration of the probe such that only the glass verdet material entered the plasma. In these shots, no drop in the current is observed. This is consistent with ablation time predictions made by simplified heat flux models and can be corrected by cladding the retroreflector material. Finally, density measurements using far-infrared interferometry show no changes in plasma density.

IV. CONCLUSION

The TIP diagnostic has been successfully demonstrated as an effective diagnostic for directly measuring internal magnetic fields in laboratory plasmas with relatively small perturbation to the plasma. Measurements can be conducted in any magnetic configuration. The frequency response of the probe and detection system is 10 MHz. Spatial and magnetic resolution of 0.5 cm and less than 200 G have been achieved. The diagnostic is ultimately limited by the time required to begin ablation of the probe surface for a given plasma energy density. Conservatively, estimates indicate that diamond clad probes could measure 1–2 keV plasmas of density 5×10^{19} m^{-3}.

Development of the diagnostic is continuing. Currently, significant, effort is being focused on developing improved algorithms for characterizing the reflected light from the probe. Better measurement of the pitch and roll, and improved modeling of the effect of pitch and roll on the polarization state of the reflected light should allow measurement accuracy of 15 G or less. Development of an effective diamond coating process is still required for high-temperature applications. The final goal for the diagnostic includes developing a probe able to simultaneously measure all three components of the magnetic field. This would allow complete mapping of the poloidal and radial magnetic profiles.

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